Master Thesis in Geosciences

Palsa development in Dovrefjell, southern Norwegian Mountains

Breakdown in a warming climate

Michaela Ferbar

UNIVERSITY OF OSLO
FACULTY OF MATHEMATICS AND NATURAL SCIENCES

Palsa development in Dovrefjell, southern Norwegian Mountains

Breakdown in a warming climate

Michaela Ferbar

Master Thesis in Geosciences

Discipline: Physical Geography, Hydrology and Geomatics

Department of Geosciences

Faculty of Mathematics and Natural Sciences

UNIVERSITY OF OSLO

2nd June 2009

Tutor(s): Leif Sørbel, University of Oslo

Ole Humlum, University of Oslo and The University Center in Svalbard

This work is published digitally through DUO – Digitale Utgivelser ved UiO

http://www.duo.uio.no

It is also catalogued in BIBSYS (http://www.bibsys.no/english)

Abstract

Palsas are peat mounds with a perennially frozen core which are mainly formed due to ice segregation. They are located in bogs in warmer (sporadic and discontinuous) permafrost zones and they are therefore sensitive to environmental changes unfavourable for permafrost.

In this study I have investigated a particular palsa in Haukskardsmyra, which is the largest palsa bog in the Dovre Mountains, southern Norwegian Mountains. Due to its southerly position, this mire is located on the climatic limit for palsa existence and therefore, can give valuable information about the reaction of palsas and the rate of degradation to climate amelioration.

The palsa has been mapped and monitored over the period 2006-2007-2008 for change detection. The palsa surface height, depth of the thawed layer over the frozen ground and snow depths have been measured. To monitor the temperature at the study site, TinyTag data loggers have been used since 2006. The data loggers have been located on the palsa surface, at 10, 30 and 70 cm depths and 1.8 m above the surface. This data, combined with temperature data from a nearby weather station, has been used to back-calculate mean annual temperatures of the palsa site until 1865. Aerial photographs from 1963, 1979, 1992 and 2002 have been investigated to trace the palsa development over the last half century.

Since 1865 the mean annual air temperature has increased by more than 1°C at the palsa site and the present mean annual air temperature is slightly above 0°C. Mean annual precipitation has increased by about 100 mm since 1923. Since 1963 the palsa bog has degraded significantly, as shown by repeated aerial photography and field studies. Over the period 2006-2008 the studied palsa has experienced a severe and violent degradation, with large parts falling into the water. Presently, both temperature and precipitation are likely too high to allow palsa development at Haukskardsmyra. Hence, the palsa bog is situated out of the climatic limit which favours palsa development.

It is likely that the palsas at Haukskardsmyra will disappear within the next 30-50 years and, by inference that also other palsa bogs in Dovre will decrease substantially in size and distribution.

Acknowledgements

First, I would like to thank my supervisors Leif Sørbel and Ole Humlum for being patient and encouraging. I have received great help and support in Oslo and in the field. A special thanks to Leif for always trying to hold contact, also when I was conspicuously absent from the University.

I would also like to thank Jon Tolgensbakk and Trond Eiken for assistance in getting access to topographical maps and data, organising field instruments and also being available when the University car breaks down on the way back from a field trip on a Sunday evening. Tone Braadland Husebye from Det Norske Meteorologiske Instituttet was helpful in providing access to an application for processing wind data. Thanks for all the helpful suggestions I got from the PhD-students of the Geoscience Institute and to the other students at ZEB for their company during the breaks. Åsgeir Seland deserves to be mentioned for his kindness and for helping out with the countless small things a student can come up with, in the course of his studies.

Thank you, Denise and Jakob, for all the time you two investigated to comment and read through the thesis and especially to Jakob who supported and encouraged me so much during the entire period of writing and conveyed comfort when things did not turn out the way I wished. Sondre similarly deserves to be mentioned for noticing my absence at all social activities during the intensive writing phase in the weeks before the deadline.

Finally, I would like to thank my parents and especially my father for always believing in me.

Blindern, 2nd June 2009

Michaela Ferbar

Table of Contents

1 Introduction

The periglacial environment harbours a diverse set of landforms. The most distinct ones such as stone polygons, pingos, palsas, and thermokarst are often associated with permafrost. Other phenomena which are native in the periglacial landscape are features developed by heavy frost weathering of exposed bedrock or mass wasting.

Permafrost is most common in the Northern Hemisphere, where more than 20-25% of the surface is underlain by perennially frozen ground (Harris 1986, French 1996; Fig. 1). Permafrost is widely defined as *"ground that remains below 0°C for two or more consecutive years, regardless of other properties such as moisture content and lithology"* (Muller 1947 in Washburn 1979). Glaciers and ice caps are excluded (Harris 1986). Most authors divide into the continuous-, discontinuous and sporadic permafrost zone, although there are disagreements about the extent of permafrost in the different zones (e.g. Washburn 1979, Harris 1986, French 1996).

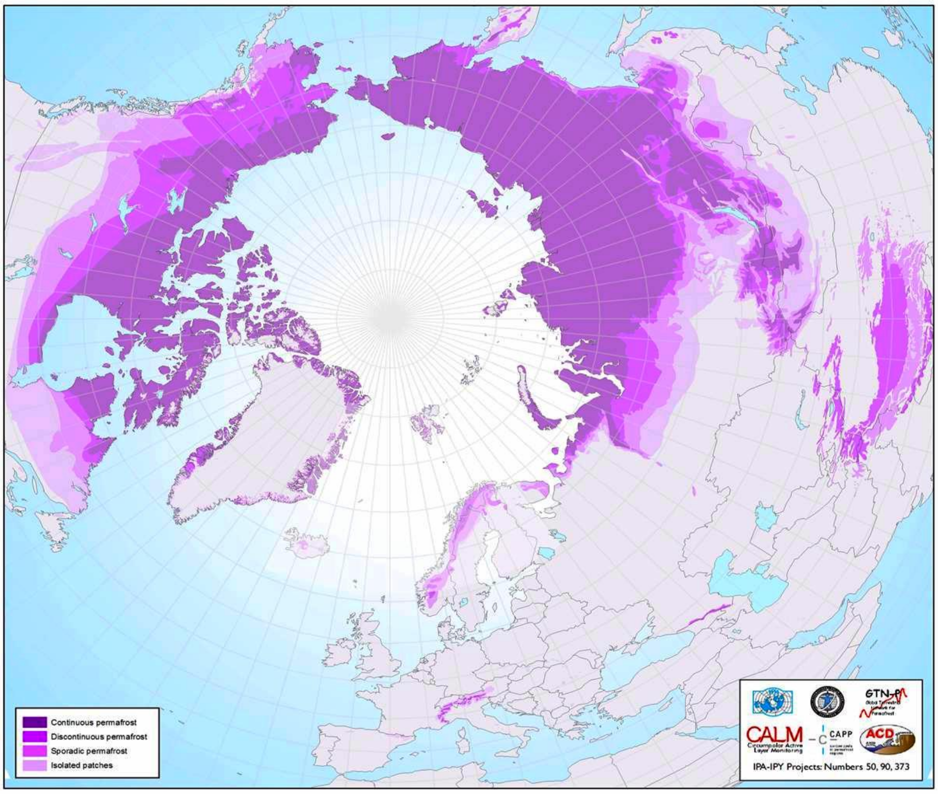


Figure 1 Distribution of permafrost in the Northern Hemisphere. Continuous permafrost, underlying 90-100% of the landscape; discontinuous permafrost, 50-90% and sporadic permafrost, 0-50% (http://ipa.arcticportal.org/ , last visited 1st June 2009).

Palsas are peat mounds which often appear in clusters with a perennial frozen core and are situated in subarctic peat bogs. They are a reliable surface indicator of permafrost and exist on the fringe from the discontinuous to the sporadic permafrost zone (Harris 1982). Usually the occurrence of permafrost is limited to the palsas themselves and cannot be found at vicinity of the mire.

Palsa bogs, which are located in an area close to the limit of existence, are sensible to climate fluctuations since also small amelioration of climate may influence their survival or decay. Therefore, palsas are discussed as climate indicators (e.g. Lindqvist 1995, Sollid and Sørbel 1998, Zuidhoff and Kolstrup 2000).

Temperatures in the arctic and subarctic regions are predicted to increase by 2.2°-5.3°C until 2090 which will cause substantial changes in the distribution of periglacial landforms (IPCC 2007). Therefore, studies on palsa bogs in marginal positions can give valuable information about the time span a palsa needs to be completely free of permafrost. The results of such studies may be used to estimate break-down rates for other mire areas such as the vast subarctic wetlands existing in Siberia, which are considered to be a reservoir for carbon (Gorham 1991, French 1996).

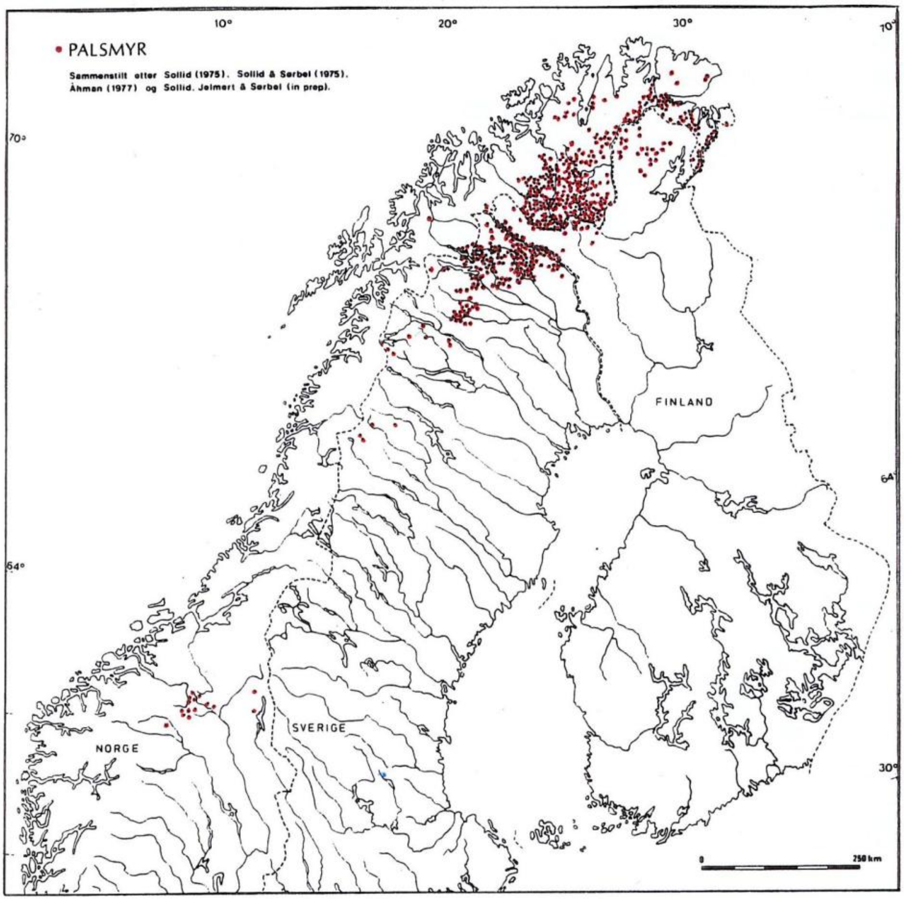


Figure 2 Distribution of palsa bogs in Fennoscandia (Lie 1996, modified from Sollid and Sørbel 1998).

In Fennoscandia, the highest density of palsa bogs can be found in the northernmost provinces of Norway, Sweden and Finland (Fig. 2). Areas with a more continental climate in the wind shadow of the Caledonian mountain range offer favourable conditions for palsa development. The southernmost location in Norway where palsa bogs can be found is in the mountain climate of the Dovre region. However, the palsas are somewhat smaller than their northern counterparts. The largest palsa bog in this area is Haukskardsmyra which is located in the Folla valley.

1.1 Previous studies

Only a few detailed studies of Haukskardsmyra have been carried out and they are mainly based on the work of two Hovedfag students from the University of Oslo as well as observations by Sollid and Sørbel (1998).

In the summer 1976, Jelmert (1978) investigated several palsa bogs in the Dovre area which is located south of the highway E6. Jelmert (1978) concentrated on the description of the mires and the specific palsa complexes and to which extent the permafrost is retreating. Special attention was paid to thermodynamic processes and the energy balance of the palsas and their surrounding.

Lie (1996) presented detailed observations of Haukskardsmyra and Haugtjørnin. Lie's thesis focus on the palsa distribution in the studied area and the changes the bogs have underwent since 1963. Lie used the vegetation as an indication for the moisture ratio and to estimate the age of these landforms and concluded that vegetation is a useful device for permafrost occurrence.

Sollid and Sørbel (1998) discussed the reliability of using palsas as climate indicators and the importance of investigations done at palsa mires positioned in marginal areas. An earlier article from Sollid and Sørbel (1974) presents a detailed study of several smaller palsa bogs near Haugtjørnin which provides an important insight of palsa distribution and development of the area.

Since degradation of Haukskardsmyra has been observed earlier and suggestions of its future fate have been given, it is of particular interests to proceed studies at this mire, document changes and to confirm or disprove predictions.

1.2 Research questions

The aim with this thesis is to understand and document the climatic and geomorphological processes which affect a specific palsa in Haukskardsmyra.

On the small-scale, the work includes a detailed study of degradation processes by field measurements, mapping, and monitoring of the palsa and an evaluation of their significance for decay. Furthermore the intention has been to investigate the long-term development by analysing aerial photographs from the last 40 years and to examine whether palsa build-up or decay can be correlated with the climatic conditions of the last century.

2 Study area

The investigated area is located in the central part of Southern Norway at 62°08’53” N and 009°22’36” E (Fig. 3). Haukskardsmyra is situated right below the tree line and is characterised by a mountain climate influenced both by continental and maritime weather conditions. The mean monthly temperature for the period 1923-2008 ranges from 6°C in July to -8.5°C in January. The mean precipitation during the same time span is rather low (450 mm/year) due to the position in the wind shadow of high mountains blocking humid air masses coming from the sea.

Due to their marginal location, palsa mires on Dovrefjell are sensible to temperature changes (e.g. Matthews et al. 1997, Sollid and Sørbel 1998, Luoto and Seppälä 2003). Located at an altitude of 1050 m a.s.l. Haukskardsmyra also belongs to the lowest lying palsa mires in this area. The Haukskardsmyra has been investigated in previous studies and hence, offers a good location to document environmental changes and their effect on a palsa mire. My studies focus on one specific palsa in this bog.

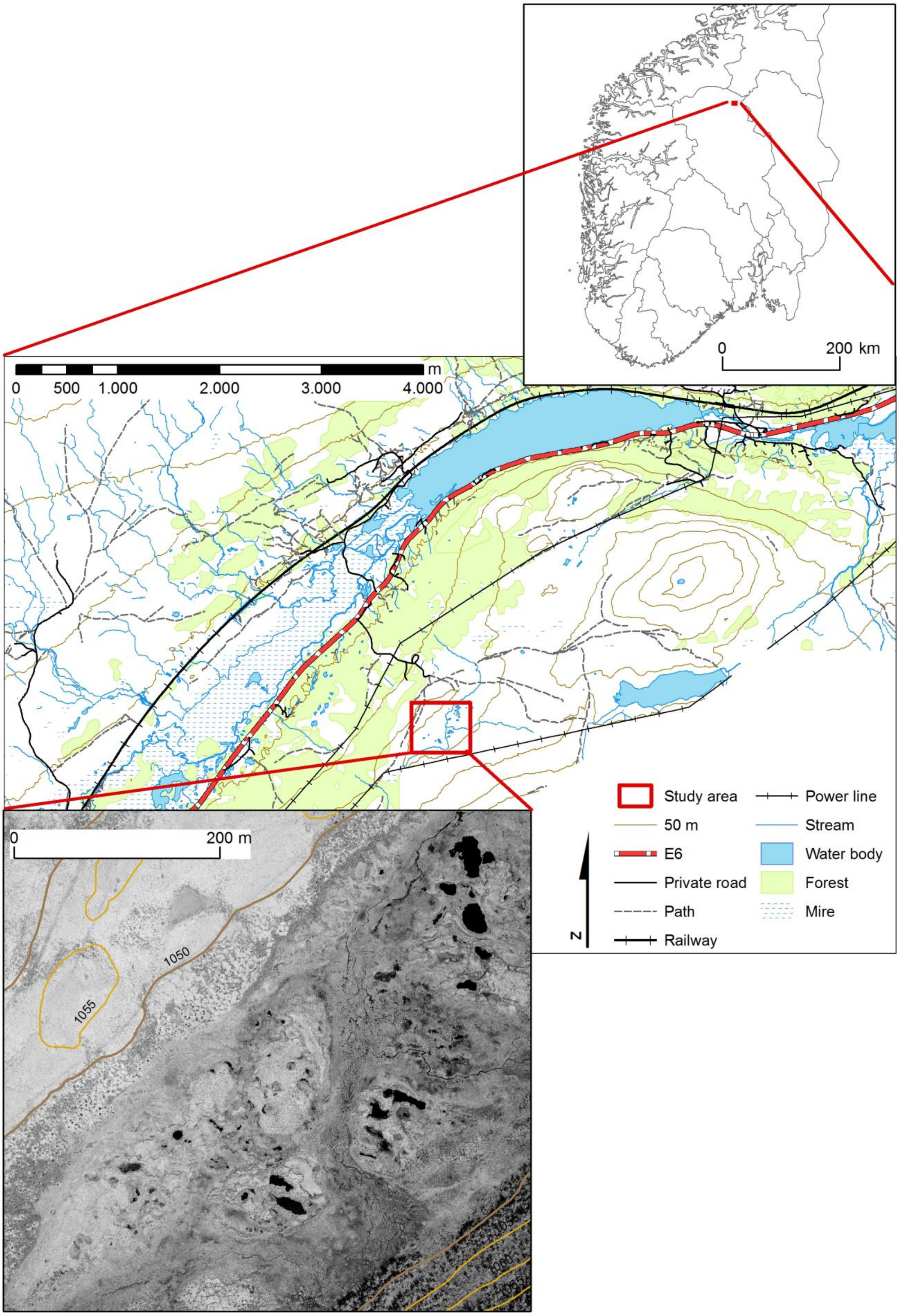


Figure 3 Location of the study area (Topographical data from Statens Kartverk).

2.1 Geomorphology

The entire area is characterised by a thick layer of loose, partly sorted, material of glacial or glaciofluvial origin which locally can reach great thickness (Sørbel and Tolgensbakk 2006). Vast bogs and wetlands in the wide valley bottom of the Folla valley and on shallow depressions along the slopes have developed due to these fine grained sediments. This U-shaped valley is running from southwest to northeast and various glacial and periglacial landforms such as glacial lineations formed by the Scandinavian ice sheet can be found (Follestad and Fredin 2006). Several Drumlins are situated in the Fokstumyrin and west of Fokstua a cluster of elongated ridges of various lengths consisting of unsorted moraine material is located (Sollid 1975). Dovrefjell was covered by the inland ice sheet and it has been suggested that the highest peaks like Snøhetta may have been Nunataks (Sollid 1975, Nesje et al. 1988). However, a growing body of research indicate that the southern Norwegian mountain region, probably including the highest peaks, have been ice-covered and preserved under non-erosive cold based ice (Sollid and Sørbel 1994, Kleman and Hättestrand 1999, Juliussen and Humlum 2007).

Permafrost seem to be favoured on north-facing slopes and permafrost features such as stone polygons and solifluction lobes are common (Jelmert 1978, Sørbel and Tolgensbakk 2006).

2.2 Meteorological observations

Weather data from Det Norske Meteorologiske Institutt (DNMI), freely accessible via their homepage www.eklima.no, has been analysed. A weather station is located at Fokstua, a few tens of meters besides the E6 highway, at 973 m a.s.l. (80 m lower than the study area) and the distance to the study area is about two kilometres. Due to different measurement methods and – not yet – configured data, not the entire range of data can be used from 1923 on. The full dataset is available from 1938, growing more detailed towards today.

2.2.1 Mean annual air temperature (MAAT)

As displayed on figure 4, the MAAT rose more than 1° during the period 1923-2008. Until 1965 the MAAT is characterised by above-average as well as a range of relatively cold years.

The general trend for the period 1935-1965 shows a temperature decrease. 1965 was the last year in the measurement period with a MAAT below -1°. After this breakpoint the trend reversed and the MAAT increased only interrupted by a few colder years around 1980 and mid 1985. The subsequent twenty years are again dominated by relatively warm years.

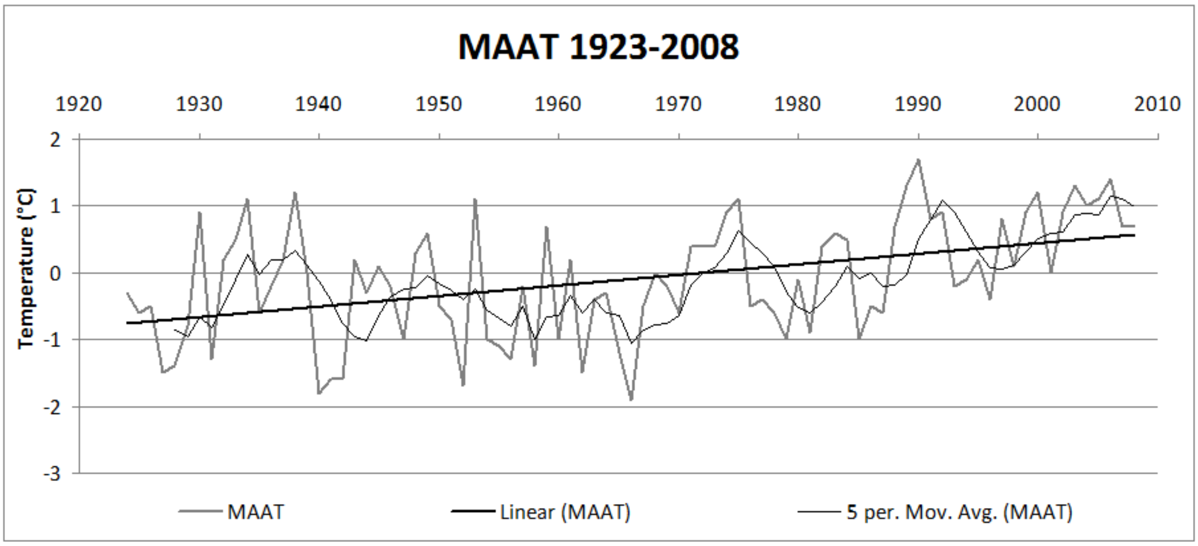


Figure 4 MAAT for the Fokstua weather station from 1923-2008.

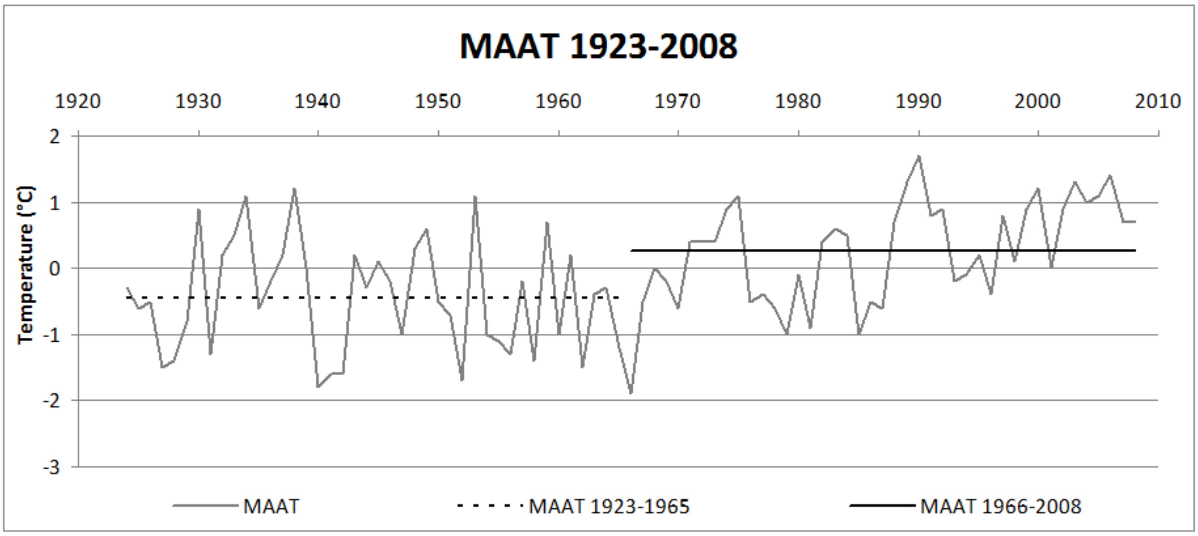


Figure 5 MAAT for the Fokstua weather station from 1923 - 2008.

The dataset can be divided into two main periods (Fig. 5). The average MAAT from 1923-1965 is around -0.5° and no clear trend is noticeable. From 1966 until 2008 a dramatic temperature rise occurred and resulted in a mean temperature for this period slightly above 0°C.

2.2.2 Temperature during the winter half-year

In figure 6 the average of all months with a mean monthly temperature (MMT) below 0°C (Nov.-April) is displayed for the period 1923-2008. On a general basis the dataset can be divided into three periods. The first period lasting from 1923 to approximately 1940 is characterised by relatively warm temperatures. A second period 1940-1970, is cooler and shows a slight temperature decline. The average temperature of this time span is about 1° lower than the average temperature of the first period. The last period, starting around 1970, reflects the same remarkable temperature increase as the MAAT. It also shows the same two peaks in the early 1970s as well as around 1990. As an example, the mean temperature for January was chosen (Fig. 7), since winter temperatures are expected to react strongest to climate change (ACIA 2005, IPCC 2007). In fact, January had the strongest trend and a temperature rise of approx. 3°C can be observed. For the MMT for February a similar rise can be observed. The figures for the MMT for all month from 1923-2008 can be found in Appendix A on the Appendix CD.

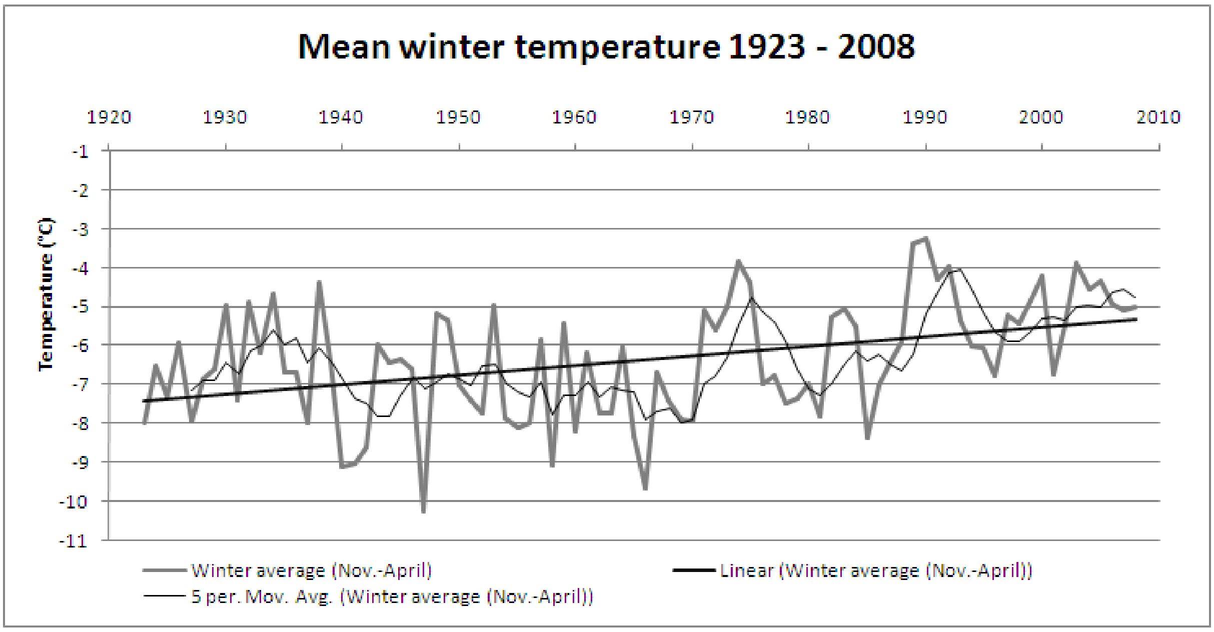


Figure 6 Mean winter temperature (Nov.-April).

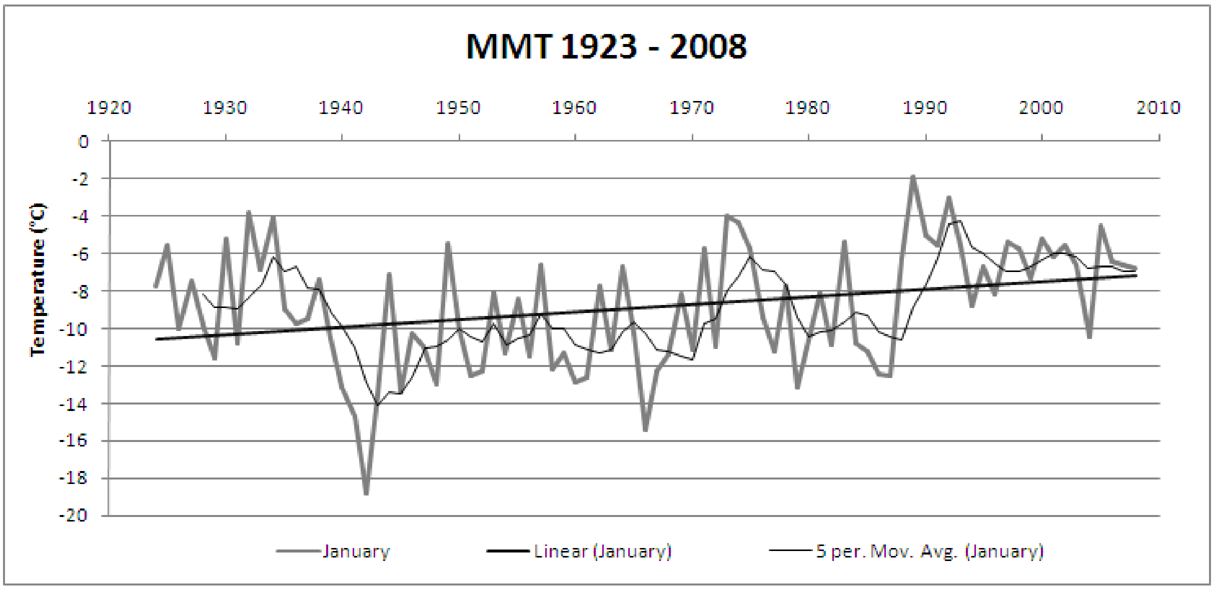


Figure 7 Mean monthly temperature for January from 1923-2008.

2.2.3 Temperature during the summer half-year

"Summer" in this context is defined as all months with an average temperature above 0°C (May-Oct., Fig. 8). From the beginning of the record until the late 1930 a clear upward trend is noticeable (Fig. 8). This time span is also characterised by a relatively high variation between single years. A lowering of the average summer temperature was registered during the following years, but during the late 1940s another slightly warmer period was reached. From then, temperatures were pretty much stable until the 1990s when a drop was recorded. Since 2000 a weak rise can be observed. Although the MMT for July shows some minor changes, the general trend from 1923 to 2008 has been stable (Fig. 9). Both during autumn and spring the trend seems to flatten towards summer. The summer month seem therefore least effected by the warming. The diagrams for the remaining months can be found in Appendix A on the Appendix-CD.

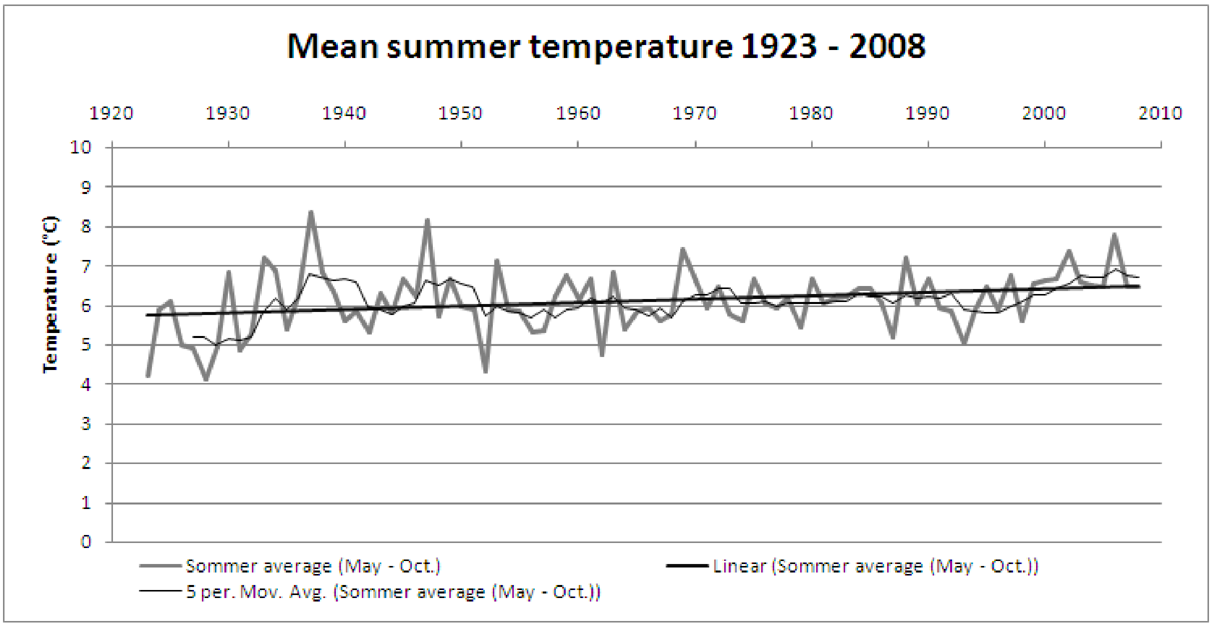


Figure 8 Mean summer temperature (May-Oct.) from 1923-2008.

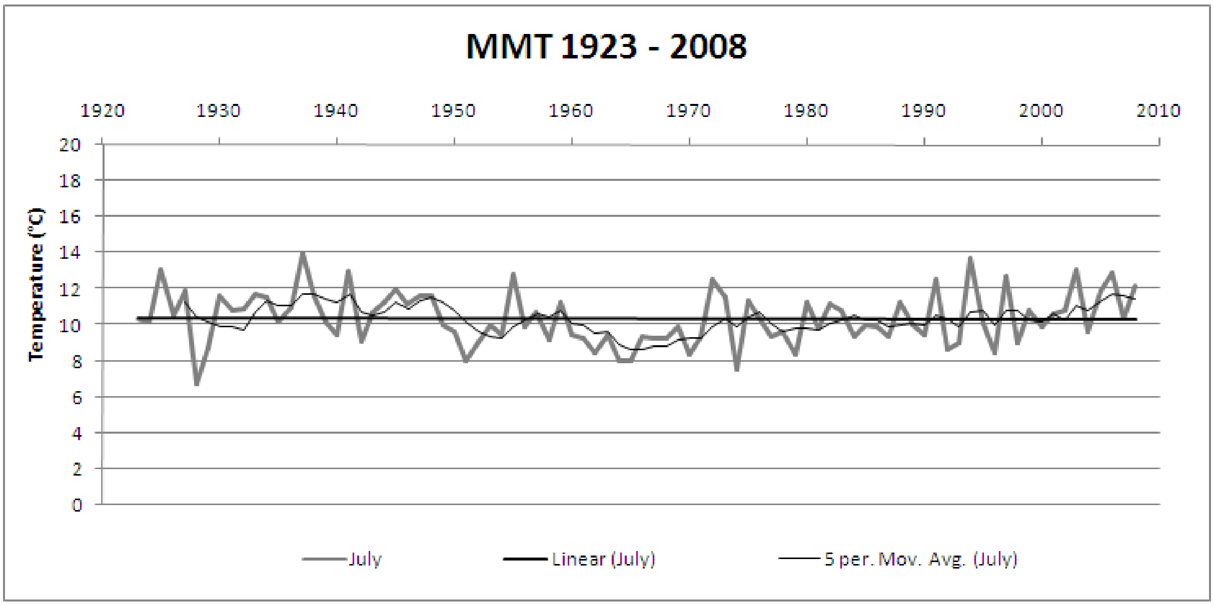


Figure 9 Mean monthly temperature for July from 1923-2008.

2.3 Precipitation

The term winter precipitation includes the sum of precipitation from November to April while summer precipitation represents the sum of precipitation from May to October. This differentiation is made on the basis of the assumption that due to a MMT of below 0°C from November to April, most of the precipitation in the winter interval falls as snow.

As shown in figure 10, precipitation is much higher during summer than during winter. The trend from 1923-2008, however, is slightly positive for both seasons and also the 5-year running average displays similarities in the variations. The beginning of the 1930s was characterised by relatively little precipitation which was followed by a quite stable period until the 1970s. The subsequent ten years display again a series of years below the normal, which is calculated to 450 mm for the entire time span. During the late 1980s precipitation lay above the average, but decreased in the early 1990s.

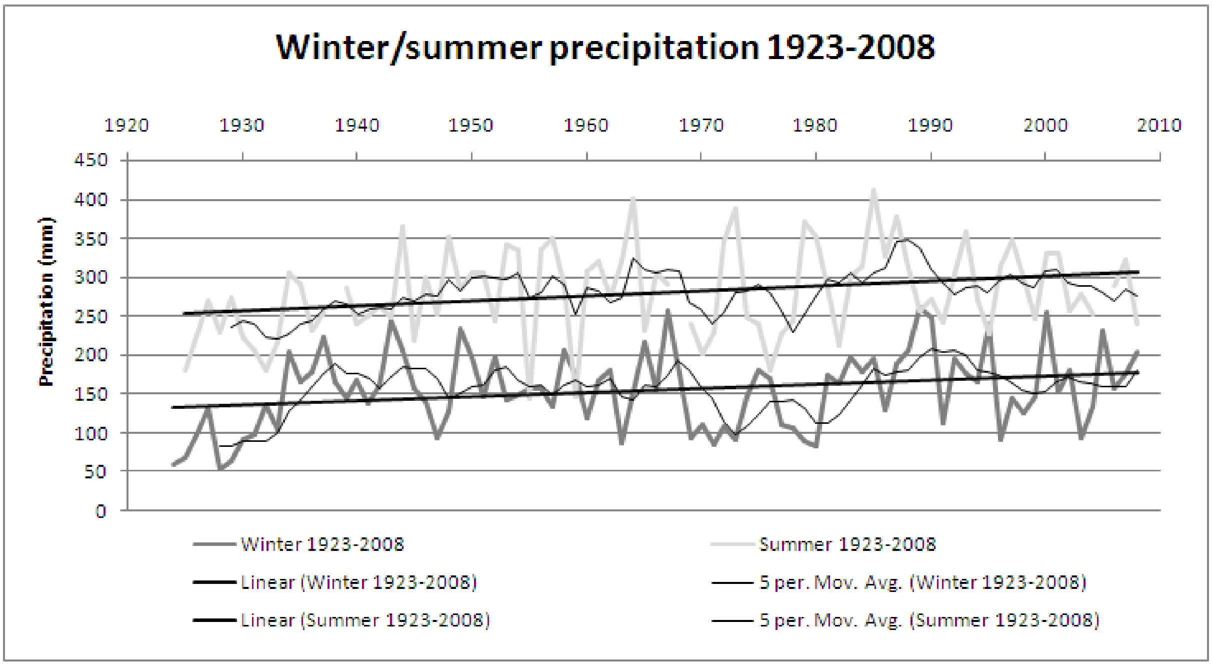


Figure 10 Seasonal precipitation from 1923-2008.

On a monthly scale, the summer months June, July and August have a much higher range and it can fall as much as 150 mm per month (Fig. 11.) This stands in contrast to the winter half-year (Nov.-April) for which monthly precipitation rarely exceeds 75 mm and mostly has an average around 25 mm. July is the only month for which a negative trend can be observed. The figures showing the mean monthly precipitation can be found in Appendix B on the Appendix-CD.

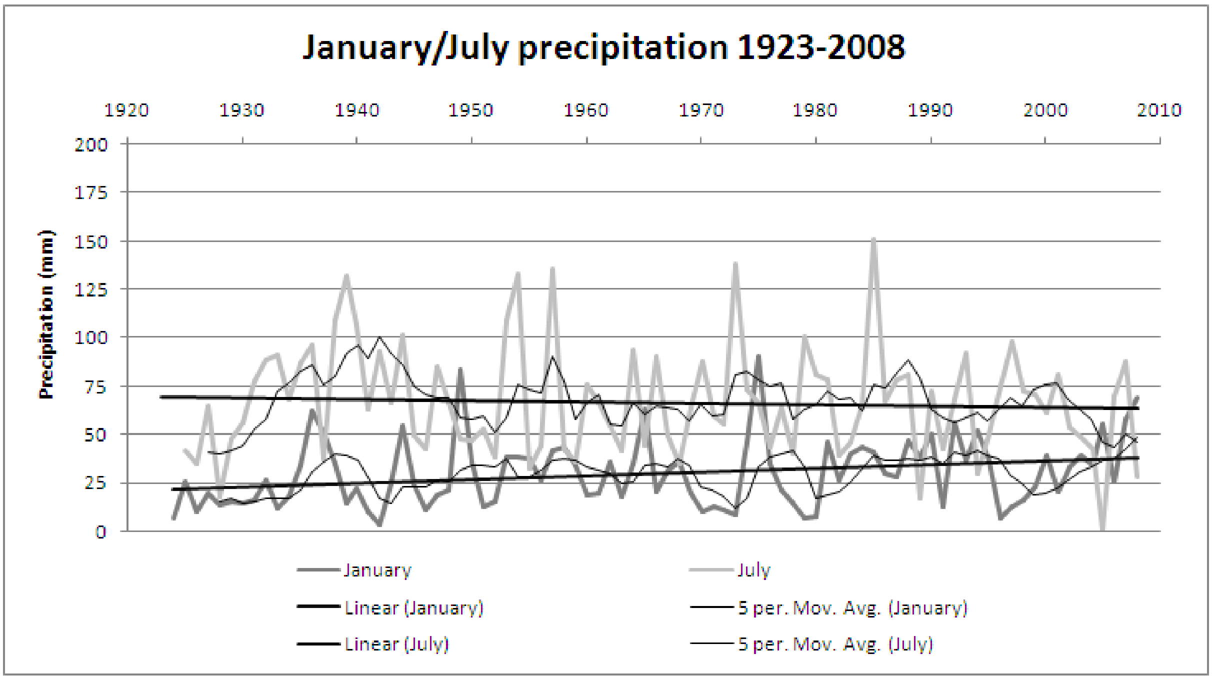


Figure 11 January and July precipitation from 1923-2008.

2.4 Wind

Figure 12 gives an impression about the main wind distribution and frequency of wind speed at Fokstua during the last 40 years. The dominant wind directions are winds from WSW-SSE. The highest wind speeds are recorded from S and SE. In order to find changes over time and seasons wind rose diagrams were created for the winter and summer season (1938-1967 and 1968-2005) as well as for all month from 1968-2005 and January and July from 1938-1967.

Winter wind is the main factor for snow distribution on a mire and, therefore, considered to play an important role in palsa development and evolution (e.g. Seppälä 1982a, 1986, 1995). The January wind data has been chosen to represent winter wind conditions but all diagrams can be found in Appendix C on the Appendix-CD.

Between 1938 and 1967 (Fig. 13) the predominant wind direction for January clearly follows the Folla valley from SSW and NNE. The highest frequency of strong winds (> 10 m/s) is recorded from SSE and S. Calm periods are common. The predominant wind direction in the period from 1968-2005 is no longer determined by local topography and changed to SSE (Fig. 14). Wind directions in this period in the sector WSW-S are nearly equally distributed. The highest wind speed and the highest distribution are recorded from S and SE.

The strong local wind pattern along the valley (SW-NE) can be observed during all 10 year winter time-spans which were plotted for 1938-1967. From 1968-1997 a SE dominated pattern was established.

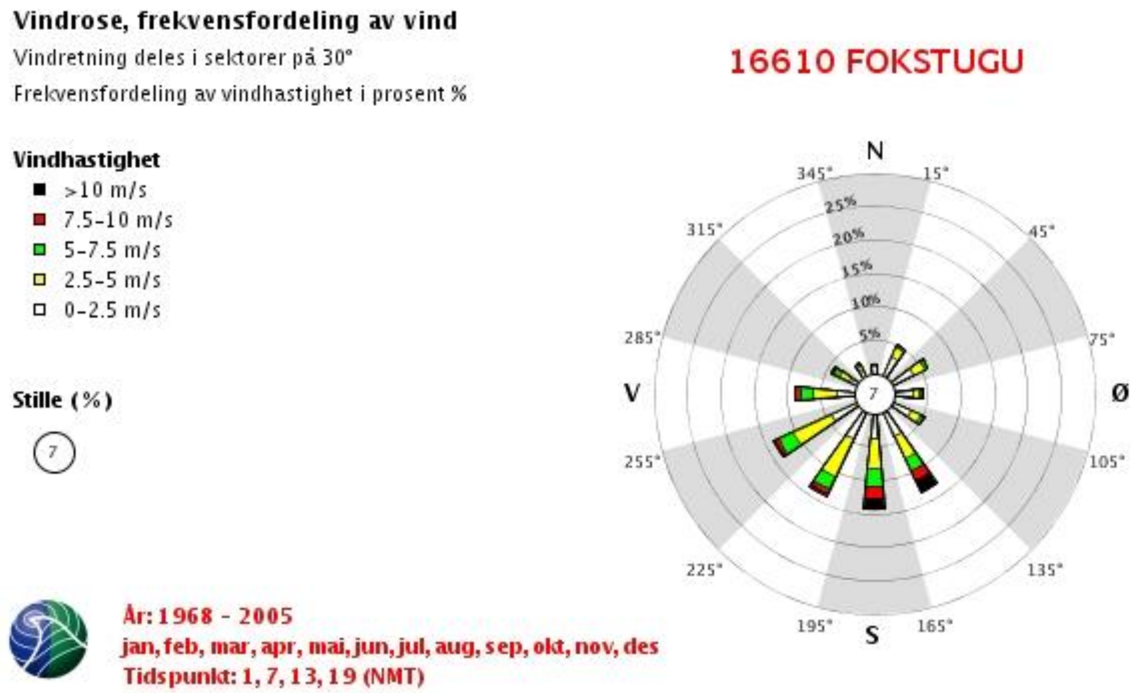


Figure 12 Mean annual wind speed and wind direction from 1968-2005.

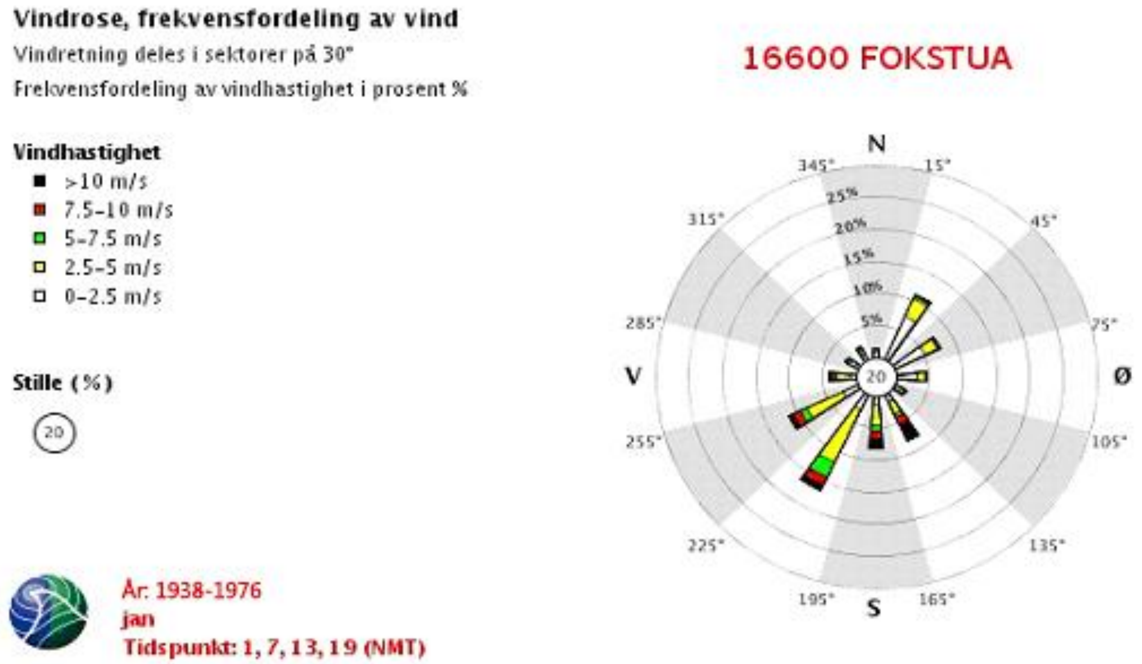


Figure 13 Average January wind speed and wind direction for the period 1938-1967.

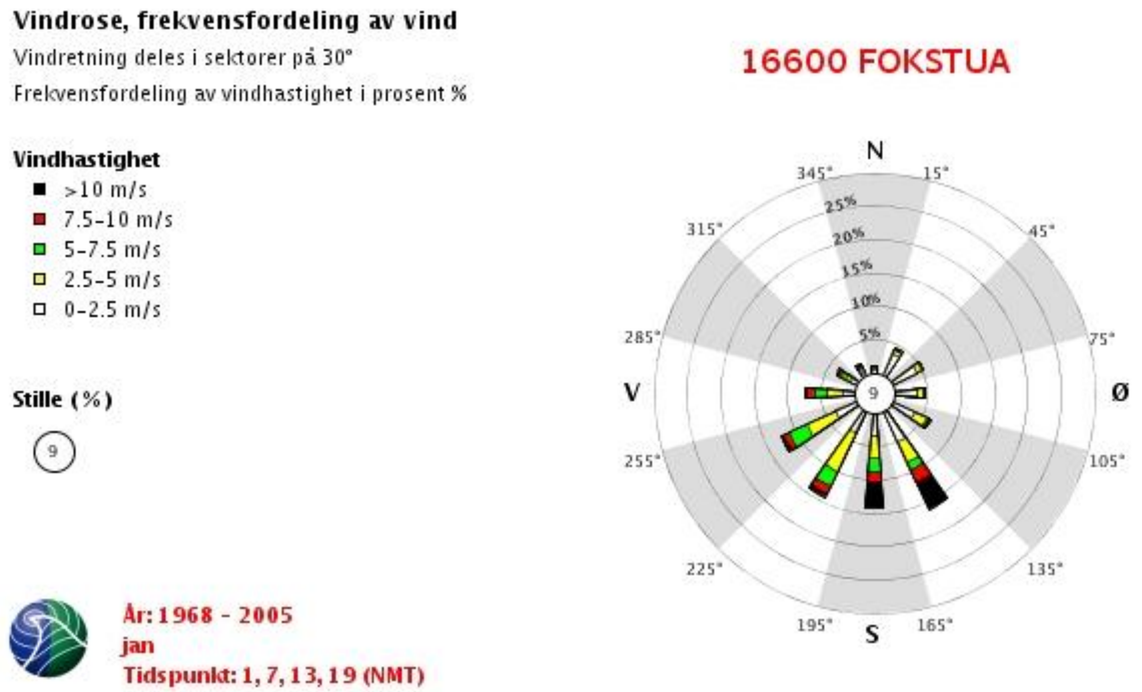


Figure 14 Average January wind speed and wind direction for the period 1968-2005.

3 Theory

3.3 Palsa

3.3.1 Definition “palsa”

The word “palsa” is of Lappish-Finnish origin and means a “peat hummock with a frozen core, rising above the surface of a mire” (Seppälä 1972, 1988b). The term got adapted by scientists, and as discussed by Seppälä (1988b) and Lundqvist (1969) has widely been used in a morphological descriptive context without referring to the evolution. Since the end of the last century, it became more common to also include the genesis in the term “palsa” (Seppälä 1988b, Pissart 2002). This, of course, postulates that the genesis of the investigated feature is known.

However, the term “palsa” has been discussed widely in the literature but there is – still – no general agreement on the exact definition. Seppälä (1982a) points to the formation of a palsa by *“ice segregation and frost penetration and a subsequent heave of the ground surface”*. He also suggests to restrict the term to “true” palsas and not to use it for other frozen peat mounds with a different genesis (Seppälä 1988a, 1988b). Peat cover is a prerequisite for Seppälä (1972, 1988a, 1988b) although the core can be of silty material. Åhman (1976, 1977) also uses the term for mineral “palsas”, which are of the same genesis as the “classic” palsas but without an insulating surface peat layer. To describe such minerogenic mounds Harris (1993) introduced the term lithalsa.

Based on Van Everdingen (1988), Pissart (2002) came up with a more recent definition. He refers to *“Perennial mounds covered by peat, situated in the discontinuous permafrost zone and due chiefly to segregation ice fed by cryosuction”*. Anyhow, it is Van Everdingen who mentions that also other factors such as size and a location in wetlands must be fulfilled. Åhman (1977) ranged the height from about 0.5-10 m and Washburn (1983) and Harris (1998) added that it must be a minimum of 2 m in average diameter.

In this paper I use the term palsa for features which are

- Perennial frost mounds
- Covered by a distinct surface peat layer
- Formed by ice segregation fed by cryosuction[1]
- from about 0.5-10 m in height and minimum 2 m in average diameter
- Located in the sporadic- or discontinuous permafrost zone
- Situated in a wetland.

I agree with Van Everdingen (1988), Pissart (2002) and Seppälä (1988a) that features, with similar morphological characteristics, but different genesis should either be compiled under terms like e.g. “frozen peat mound”, “frost mound” or “palsa-like feature” or new subcategories may be introduced.

3.3.2 Palsa genesis, development and erosion processes

Based on his observation of coexisting degrading, stable and growing palsas, Lundqvist (1969) concluded that their evolution is subject to a cyclic development. He stated that their decay only in some instances may be due to a slight climatic warming. A cyclic evolution of palsas has been discussed in the literature by e.g. Svensson (1962), Wramner (1967), Åhman (1977), Seppälä (1982a, 1986, 1988b) and Zoltai (1993).

Seppälä has often stated that the initiating factor is a thin snow cover (Seppälä 1982a, 1986, 1990, 1995, 2004) and wind drift is assumed to be the main agent (Fries and Bergström 1910). Zuidhoff and Kolstrup (2005) report a clear link between snow depth and vegetation and suggest that different plant species may cause varying snow depths. A shallower snow cover allows freezing penetrating deeper than the summer heat is able to thaw (Fig. 15, A). Seppälä proved this hypothesis by removing snow of a mire surface several times during three consecutive winters and creating a man-made embryo palsa (Seppälä 1982a, 1995). This artificial palsa reached some 30 cm in height by the end of the third winter.

[1] *“A suction developed in freezing or partially frozen fine-grained materials as a result of temperature-dependent differences in unfrozen water content”* (Van Everdingen 1988).

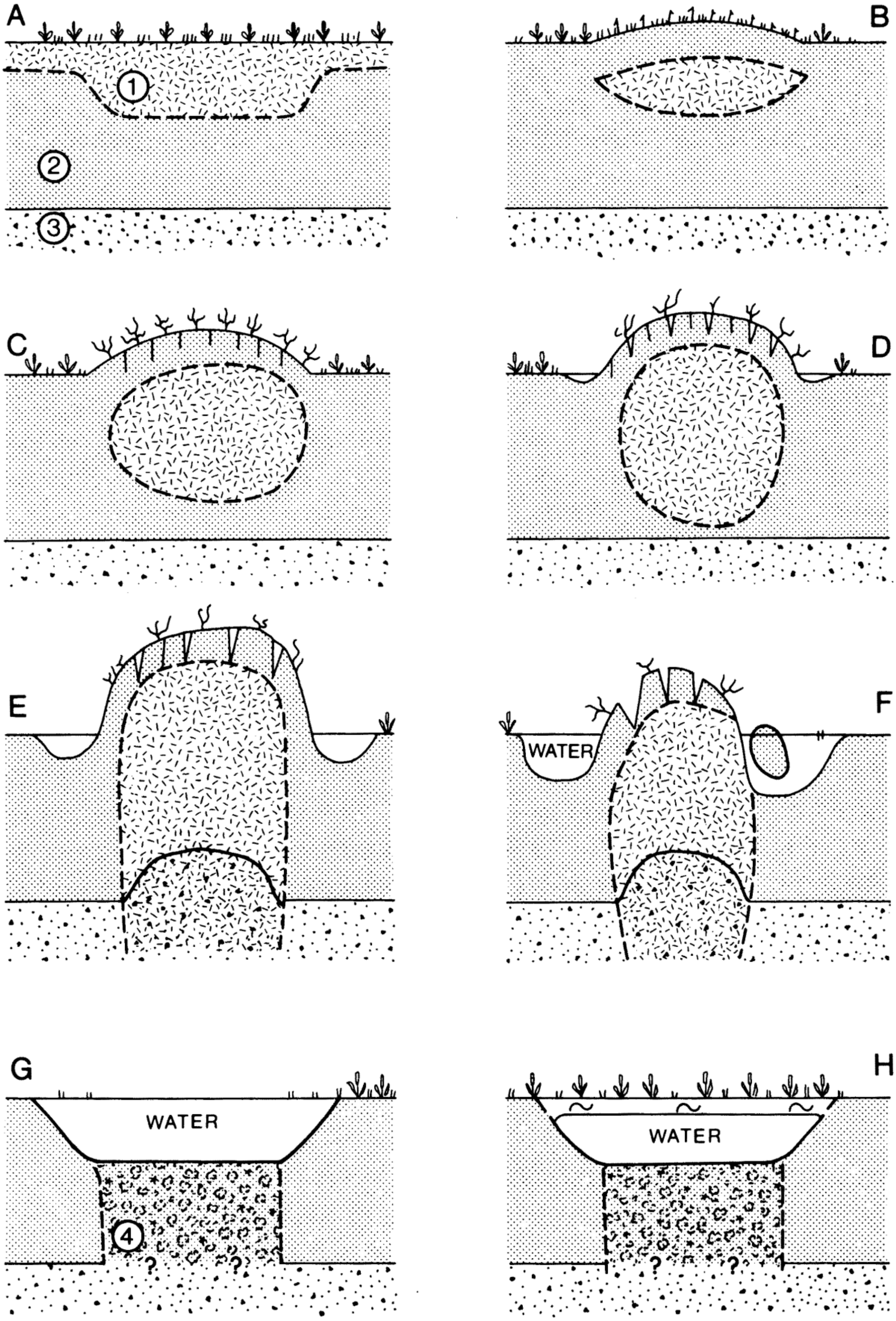


Figure 15 Cyclic development of a palsa. (1) Frozen core. (2) Unfrozen peat. (3) Silty till. (4) Decomposed unfrozen peat. A. Beginning of thawing season. B. End of first thawing season (Seppälä 1986).

Based on his field studies he presented his concept of cyclic palsa development (Fig. 15, Seppälä 1982a, 1986). During the first years, a shallow frost body establishes which increases in height and grows towards the sides in the beginning. The size of the palsa is determined at this stage. After the surface is raised above the mire this embryo palsa will be more exposed to wind drift and its top will have a somewhat shallower snow cover than its surrounding. Frost can then penetrate deeper and the growth will accelerate due to freezing of pore water and ice segregation. As the upheaval continuous, the impact of wind in blowing the top surface free of snow in winter and drying the peat in summer becomes more extensive. During winter, snow accumulates along the sides and prevents the frost layer from deepening. The palsa has reached its maximum area. However, the frozen core reaches the mineral subsoil and rise will proceed until the palsa stands well above the bog surface (Fig. 15, E). By this time, the edges are steep and covered with open cracks. When the critical point is reached, the pieces of the sides will break off or slide down. Block erosion has started. Often, pools around the palsa have developed. The palsa might be exposed to deflation and rain erosion due to missing vegetation. In another scenario, the palsa thaws slowly from the bottom and sinks back into the water. Thermokarst and collapse forms characterise an old palsa. The remnants of a palsa are unfrozen and may either look like a low circular rim ridge, a round open peat surface or pond. After peat has invaded the open surface, a new palsa may grow on the same site.

Åhman (1977) focuses mostly on the degradation and gives the erosional ability of the water and the influence of the silty material beneath the peat layer a greater importance. In contrast to Seppälä (1986), who concludes that the area of a palsa is more or less decided within the first few years and then stays stable until the break-down starts, Åhman presumes a frozen base area which extends somewhat beyond the edges. The minerogenic core is covered by peat. The permafrost table, which first was situated in the peat layer retreats when the surface gets eroded and establishes in the mineral substrate. As a result, a “palsa lagg” (a water pool; Lundqvist 1951) develops. The thermal capacity of the water causes further degradation of the palsa by enhanced thawing. Lowering of the palsa and melting of the frozen core occurs on a relatively small part where block erosion dominates. The remaining part of the palsa can stay undisturbed. Åhman (1977) and Wramner (1973) argue that palsas with a mineral core erode faster than the ones which only consist of peat. Although the break off of peaty blocks is more intense, the mineral soil hardly joins the sliding material, stays at the base of the palsa and sinks back to the mire bottom after the decay of the palsa (Åhman 1977). Åhman (1977) concludes that the faster erosion is caused by the underlying minerogenic material which on the one hand has higher heat conductivity and on the other hand includes (also in the frozen state) a considerable amount of non-frozen water.

In accordance with Lundqvist (1969) and Seppälä (e.g. 1982a), Åhman (1977) suggests that this cycle is the reason for the collapse of individual palsas rather than changes in climate.

The degradation of a palsa is an interaction of the different erosion processes. Cracks around the edges may develop as soon as the palsa rises and the stretching of the surface increases by further growing (Seppälä 2003, Zuidhoff and Kolstrup 2005). Palsa laggs form and melting accelerates on the edges of the palsa due to the great thermal capacity of water which absorbs between five and seven times as much insulation compared to the adjacent soil (Harris 2002). This causes an undermining of the frozen sides and results in a down sliding of the lowermost peat layer. Further thawing feeds the pond (Harris 2002) and subsequently, peat blocks loosen and break off from the edge (e.g. Svensson 1962, Wramner 1967, 1973, Åhman 1977). The material of the blocks dissolves in the water, but is not enough to fill the lagg. Hence, melting continues. Seppälä (2003) considers block erosion to be the main destructive factor.

Wramner (1967) concludes that freezing of the palsa lagg and the coherent expansion of the ice layer causes a weak zone in the horizontal peat of the palsa. The upper layers glide down. Palsa laggs and block erosion are not as common along palsa plateaux (Åhman 1977). Figure 16 shows the block erosion as described by Åhman (1977).

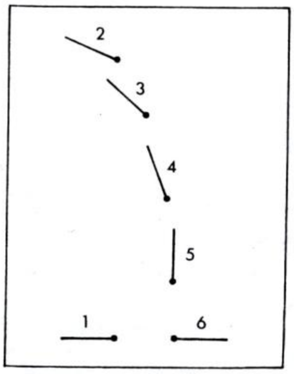


Figure 16 The movement of peat within the palsa evolution and degradation. (1) The primary position. (2) The uplifted position after rise. (3-5) Down-creeping of the palsa side. (6) The eventual peripheral end position (Åhman 1977).

The vegetation and the peat surface on top of the palsa is exposed to erosion by drifted snow or ice crystals driven by high velocity winter wind (Seppälä 2003). Åhman (1977) describes that wind erosion first starts on the blown free summits and, by displacing vegetation advances towards the sides. Loss of vegetation makes the palsa more sensitive to wind- and rain erosion as well as thawing. Åhman (1977) and Seppälä (2003) considers wind erosion during winter to have great erosional power but is negligible during summer.

Apart from the direct erosion of the surface, rain causes a wetting of the peat layer which increases its thermal conductivity (Seppälä 1976). Rain water penetrates down to the frozen core and accelerates melting on the frost surface. By excessive rainfall the water level of the mire and hence, the palsa surrounding ponds and pools on top of the palsa, may rise and erosion on the sides may increase.

When all these erosion processes reach a critical point they amplify each other and the palsa dies. However, different processes may be dominant at different palsas – even within the same mire.

3.3.3 Water accumulation

On palsa mires, open water bodies are common.

Just below the palsa sides, Lundqvist (1951) could often identify a narrow zone of either free water or wetter peat than the surrounding and called it palsa lagg. Wramner (1973) explains this zone by the thinning of the mire surface due to the upheaval. He acknowledges that a reduction in the volume of a palsa can be another reason, but at the same time imply that this explanation does not justify why expanding embryo palsa have a palsa lagg. Åhman (1977) suggests that a water lagg is the first sign of beginning degradation. When the palsa lagg grows, a pond develops.

On the palsa itself, shallow water-filled pits or "palsa göls" which are underlain by permafrost may develop. They are situated above the bog surface and not connected to the surrounding mire (Wramner 1967, 1973, Svensson 1962). Some of them may always stay water filled, while others may dry out within the late summer (Wramner 1973). Depending on local conditions, they can disappear again or thaw more of the adjacent ground ice, deepen the active layer and expand (Harris 2002).

After the palsa has degraded, a shallow round pond with open water will remain (Lundqvist 1969, Svensson 1962, 1969, Seppälä 1982a, 1986). Former, already melted palsa mires can be easily identified on aerial photographs by these characteristic round lakes.

3.3.4 Palsa morphology

From a mere morphological point of view, palsas can be classified in different types.

Both Wramner (1973) and Åhman (1977) distinguish between pals plateaux ("palsflak" according to Wramner), dome-shaped palsas, string-from palsas and palsa complexes. Åhman (1977) also specified esker palsas ("åspalsar" according to Åhman) which later were referred to as ridge-form palsas by Seppälä (1988b). However, a gradual change between these forms may cause the existence of transition forms.

Most common on Dovrefjell are dome palsas and palsa plateaux (Sollid and Sørbel 1998) which also characterise Haukskardsmyra. Therefore, only these types are presented here.

Dome-shaped palsas

These conical palsas represent the “classic” palsa type. According to Åhman (1977) and Seppälä (1988b) they can grow up to 7 m in height and are characterised by their single, isolated dome and circular or oval area.

Palsa plateaux

Pals plateaux are extensive palsas with a nearly plane surface. The sides are steep and rise about 1-1.5 m above the surrounding bog (Åhman 1977). The size can range from only some 10s of meters to some 100 meters. On top of the palsa, small water filled depressions are situated.

4 Methods

4.1 Field work

The main purpose of the field work was to find out how fast and to which dimension the break-down of the palsa in Location 4 (see Fig. 19 for positioning) occurs in the course of two years. The methods which were used to compare the changes became more and more sophisticated and the learning process is still continuing. Some data from 2006 is of low quality and was therefore not used in the thesis, but can be found in Appendix D on the Appendix-CD.

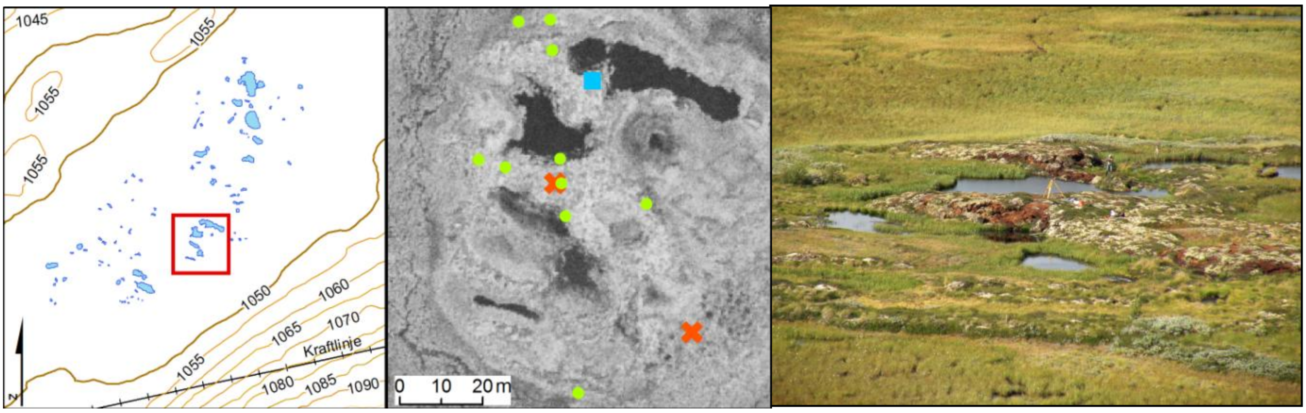


Figure 17 The position of the data loggers (red cross), the remaining reference poles in August 2008 (green dots) and a trench dug in 2006 (blue square). The photo shows the palsa towards north in 2008.

Figure 18 Burial of the data loggers in September 2006 (Photos: Leif Sørbel).

Field work was carried out in the periods 4-10.9.2006, 10-11.11.2006, 26-27.2.2007, 18.9.2007, and 23-24.8.2008. In addition, profiles measured by participants of the course 2130 – Landformer i Norden in 2006, have been considered.

4.1.1 Temperature measurements

Five TinyTag loggers were left in and around the pals on 10th of September 2006 (Figs. 17 and 18). The loggers measure the temperature once an hour (UTC+1). One was installed on a tree nearby at around 1.80 m height while the others were placed directly on the pals. One sensor remained on the surface while the other three were buried at 10 cm, 30 cm and 70 cm depth at the top of the investigated pals (Location 4, Site B). The lowermost sensor was situated right above the frozen ground surface. For downloading the data, the data loggers were changed on 11.11.2006, 18.9 2007 and 23.8.2008.

4.1.2 Land survey

4.1.2.1 Nivellement

A nivellement was used to assemble profiles of the palsa surface as well as the permafrost table in summer 2006. One longitudinal- and two cross profiles were measured. The start- and end points were measured with the help of an ordinary handheld GPS with an accuracy of plus/minus 15 m.

4.1.2.2 Total station

Both in summer 2007 and 2008, height and distance measurements were accomplished with the help of a total station and a topographical map was produced. The data was imported into a global projection with the help of differential GPS which gives an estimated precision of maximum plus/minus 40 cm in the centre zone.

The instrument was set up in a relatively stable area. The top of the pals consists of dry peat which gives in easily and therefore the position of the tripod may have moved slightly during the measurements.

4.1.2.3 Differential GPS

In August 2008 a differential GPS from NGI was brought for testing purposes. Because I lacked satisfying data from the total station for the entire southerly water line from the same year, GPS points were used in addition. The precision of the differential GPS data is plus/minus 40 cm and therefore the points were readjusted with the help of control points.

4.1.2.4 Reference poles

In 2006 poles were set up along three profiles (Profile B, C, D and E, see Fig. 29 in paragraph 5 for positioning) on the pals as well as on control points. The objective was on the one hand, to measure the distance between break edges in order to document new break offs, and on the other hand to take the snow depth along these profiles. Snow depth was measured in November 2006 as well as February 2007. However, already in February 2007 one pole which marked a point in the profile was missing. By the summer 2008 most of the poles were either missing or lying in the water (Fig. 17). Hence, the reference poles were not used as originally intended, but their disappearance/falling into the water is still useful as an indicator of the geomorphologic activity of the pals.

4.2 Remote sensing

Aerial photographs from the years 1979, 1992, and 2002 were acquired and an already existing aerial photograph from 1963 was scanned. The aerial photographs were georeferenced with the help of the 1:50 000 map from Statens Kartverk. Many of the reference points around the mire were not ideal for this purpose but the accuracy in the area of interest was weighted more important than "better" points in the far distance. However, the aerial photograph from 2002 matches best with the points taken with the total station whereas the other aerial photographs show larger uncertainties.

From the aerial photographs water bodies and the estimated distribution of the palsas in the mire were digitised. This process is liable to the resolution of the photographs, subjective interpretations and generalization and therefore, may contain inaccuracies.

Source of the aerial photographs is TerraTec AS, Statens sentralarkiv for vertikalfoto. The following aerial photographs were used:

Year	**Series**	**Number**
1963	1431	H 13
1979	2110	2809
1992	11438	19-3/11
2002	12799	13/2

4.3 Proceeding Methods

4.4.1 Terrain model

From the points which were measured with the total station a terrain model for 2007 and 2008 was created. The resolution is very good, although the model is not perfect and mistakes may occur. These nonconformities were not eliminated in order to avoid the generation of new errors. From this terrain model, height profiles of the palsa surface were plotted.

4.4.2 Meteorological data processing

The first weather station at Dombås was positioned in 1865. The data series from all following stations are coupled together which results in the longest dataset in the neighbourhood. The correlation of the overlapping temperature measured at Fokstua and Dombås is very high ($r^2 = 0.956$). Therefore, the data from Dombås could be used to extend the dataset for Fokstua back to 1865. The same procedure was applied to calculate back the air-, the surface-, and the -10 cm temperature of the palsa site. All regression analyses can be found in Appendix E on the Appendix-CD.

5 Results

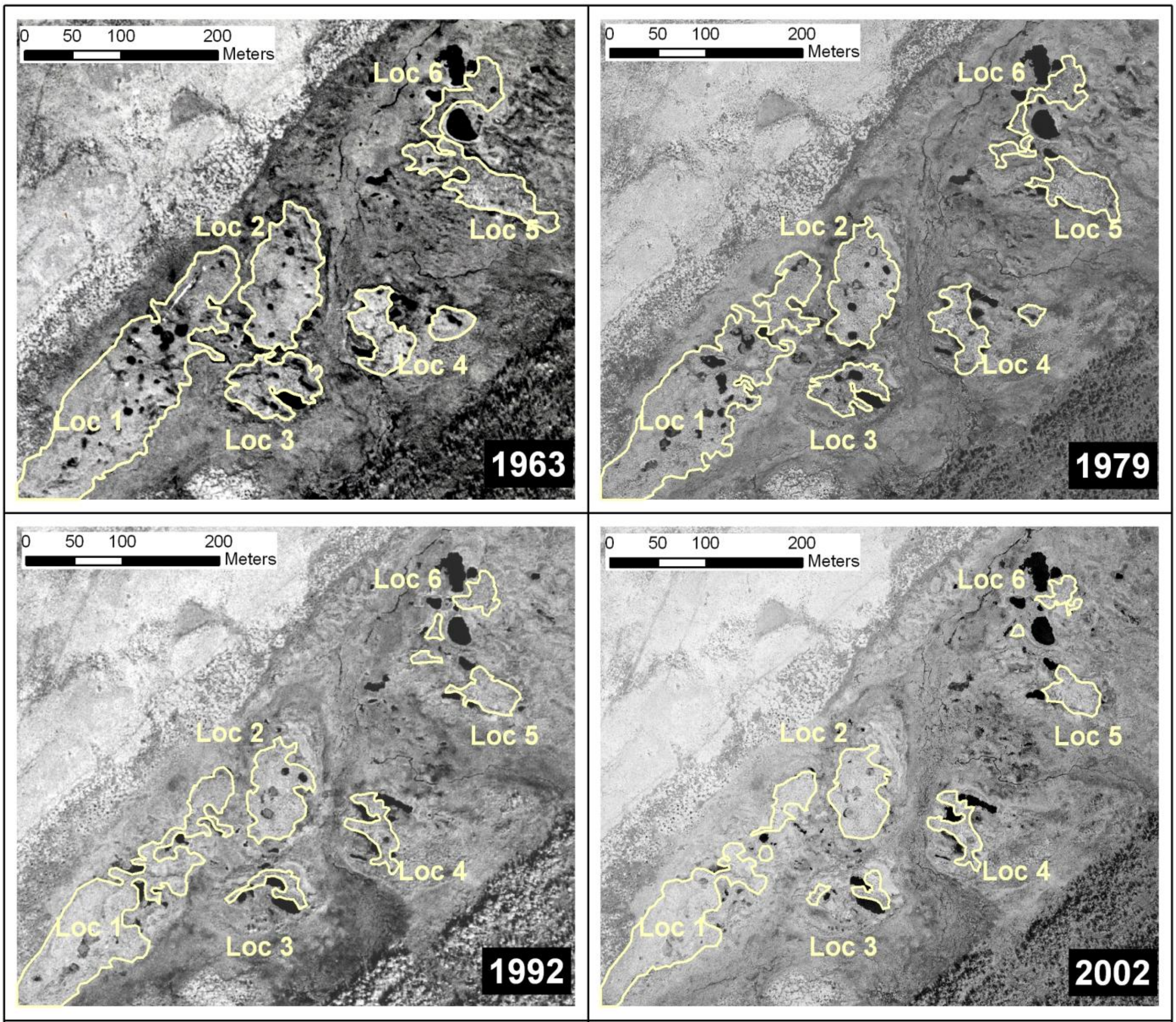
5.1 Haukskardsmyra

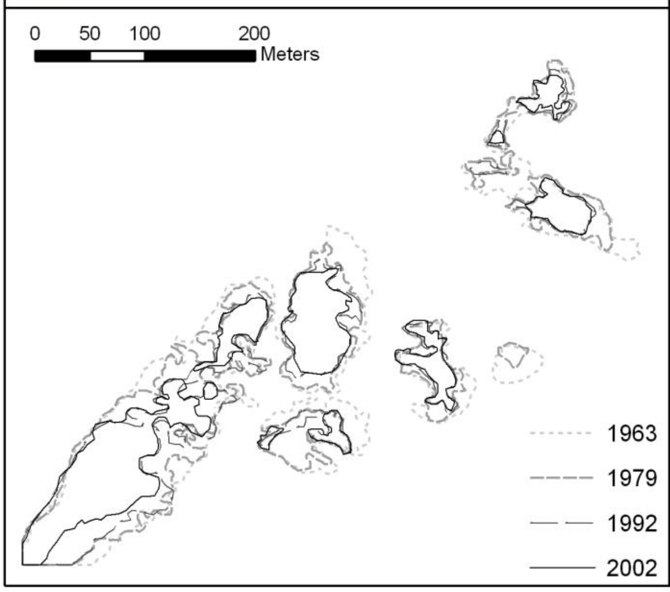
The mire is composed of six palsa complexes, of which the palsa plateaux of Location 1 and 2 (Fig. 19) are the largest. Mapping based on aerial photographs and the subsequent calculation of the palsa area shows a substantial reduction of size for all locations. Since 1963 the palsas have reduced to half their size. Break-down occurs, both when ponds establish at the sides and erode their way inward, and on top of the palsa due to widening and deepening of small pools which, in the early stages, are situated on the palsa surface. In the 1963 aerial photograph plenty of water surfaces are visible on and around all palsas.

In the elongated palsa plateau of Location 1, ponds enlarge during the time span the photographs were taken and, finally, eat all the way through and divide the plateau in two. The ponds become overgrown by vegetation. Location 2 shows a similar development. Also the palsas in the northernmost locations shrink, and the smaller ponds increased in size until 1992. Location 4, which is the area of interest, underwent substantial changes which are described in paragraph 5.2.

During the field visits, a height of more than 1 m was observed for Location 1 and 2. The slopes around the circular depressions on the palsa plateau of Location 2 were bordered by large cracks. A rise in the water level of the mire by 5-10 cm from 2006 to 2008 was noted.

The peat formation on the summits of the palsas apparently stopped completely, mosses and lichens dominate and the typical mire vegetation disappeared. This implies that these are the surfaces of old palsas.





AREA OF ESTIMATED PALSA		
1963:	46 378 sqm	100%
1979:	36 057 sqm	78%
1992:	25 377 sqm	55%
2002:	19 987 sqm	43%

AREA OF WATER BODIES		
1963:	4 930 sqm	100%
1979:	5 035 sqm	102%
1992:	4 882 sqm	99%
2002:	4 216 sqm	85%

Figure 19 Aerial photographs from Haukskardsmyra and the change of the aerial extend of the palsas from 1963-2002.

5.2 Location 4

5.2.1 Geomorphology

The palsa of Location 4 is a dome palsa which in 2008 consisted of two small domes in the northern part (Site A and B, Fig. 21) with a maximum height above surrounding terrain of about 1.7 m. The remnant of Site A has steep edges along its entire southern side. The north- and south edges of Site B are characterized by defined break edges and the branch lowers towards west. The domes are encircled by three ponds, which already have established a water exchange but not yet clearly are connected either due to vegetation or blocking peat lumps. This part is exposed to high erosional activity and is clearly in a stage of rapid degeneration.

Towards the south, the palsa flattens out and is only interrupted by a small round depression which is located in the central part. Mire vegetation has colonised it. Towards southwest the former maximum distribution of the palsa is marked with a low ridge-like rampart.

5.2.1.1 Palsa distribution

Since 1963 the investigated palsa has been considerably reduced in size, with an estimated area loss of about 70% until 2008 (Fig. 20). The ponds surrounding Site B were about 25 m away from each other in 1963 and quite stable until 1979. However, erosion proceeded fast after that and on the 1992 aerial photograph Site B is only 12 m wide. During the field visit in 2006 frozen ground was still observed in the entire side arm of Site B but its middle part was lowered nearly to the same level as the water surface. This part was waterlogged in autumn 2007 and in summer 2008 the vegetation in this area was situated about 20 cm under the water surface. The grass was still alive, indicating either lowering of the surface or water input in a recent and fast process.

The distance between the two big northernmost ponds was about 25 m in 1963 and until 1979 about 6 m of the edge was eroded by the easterly pond. Until 1992, both ponds had increased their size so that they were divided by approximately 10-16 m. By 2006 this land bridge was exposed to intense erosion and its width was reduced to less than 6 m. Two years later the middle part broke down and big peat blocks lying in the water were the only remnants.

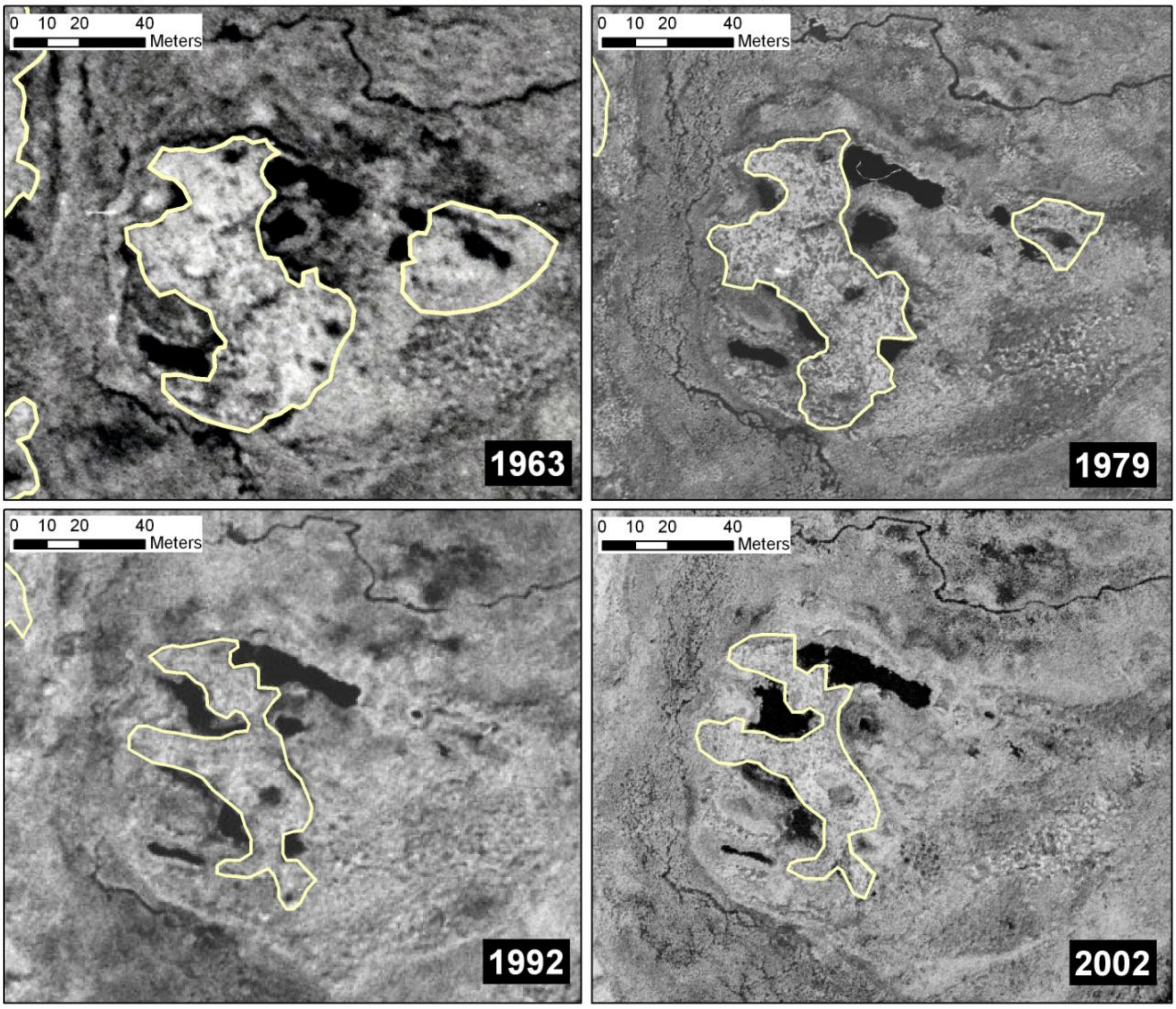


Figure 20 Aerial photograph of Location 4 and the palsa distribution.

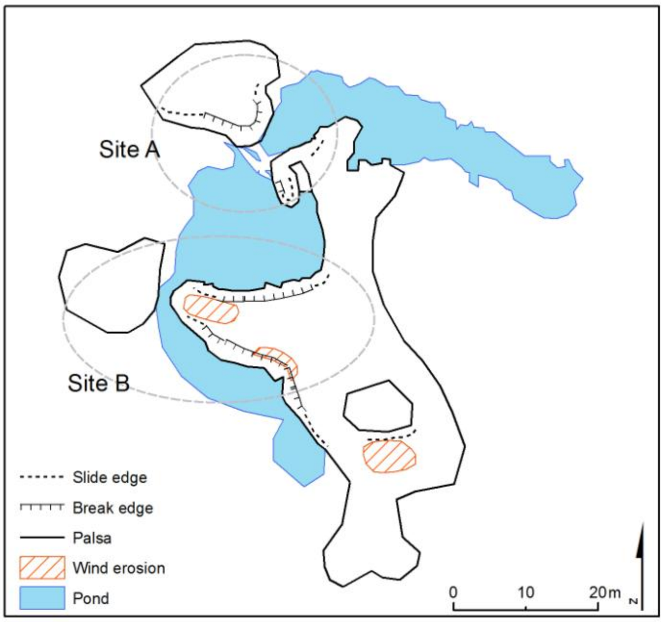


Figure 21 Map of the palsa in 2008.

The isolated eastern part of the pals degraded from 1963 on and within 1992 most parts of the ponds were invaded by vegetation. This part was levelled during the field visits.

5.2.1.2 Erosion processes

Rapid erosion - block erosion and cracks

In my thesis I decided to use the term "break edge" for all steep edges which are exposed to rapid erosional activity such as active break off of peat blocks (Fig. 22). Big blocks are found along the edges because block erosion is faster than the ability of the water to dissolve the material. The expression "slide edge" applies to all edges which have big cracks but seemingly are characterised by a down sliding process (Fig. 23). The term "erosional edge" includes both break edge and slide edge.

Figure 22 A break edge on the north-facing slope of Site B. Photo from 2007.

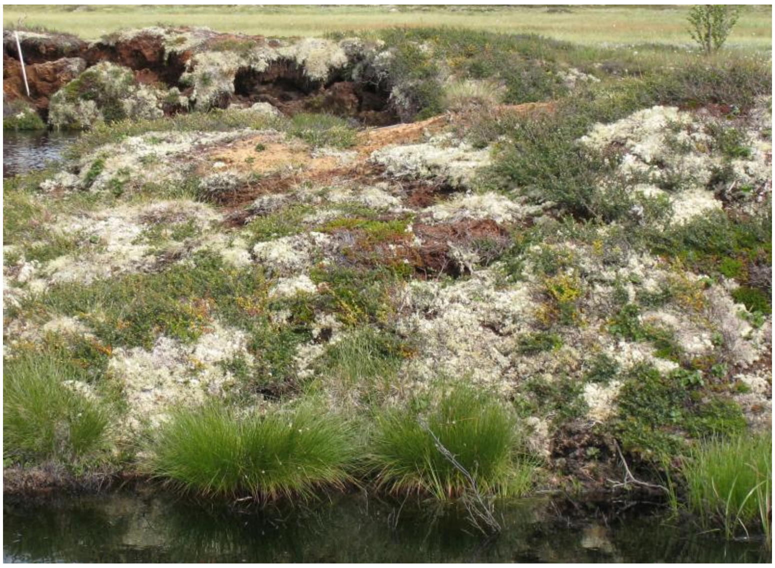


Figure 23 A Slide edge on the south-facing slope of Site B. In the background, a break edge of Site A is visible. Photo from 2007.

Based on analyses of the aerial photographs it can be assumed that erosional edges must have worked active the last 45 years. Especially the two northernmost lakes were most likely surrounded by steep edges of high erosional activity. According to Jelmert (1978) a series of undissolved peat blocks were laying in the water along the eastern edge of Site A in 1976 which indicates intensive block erosion. He also recorded that the horizontal distance from the top of the edge (1.8 m) to the pond partly fell to below one meter. This suggests that a break edge must have developed some time before 1976. Also during the field visits from 2006-2008 the innermost parts of this side were identified as break edges, which seem to phase out into slide edges towards the sides.

Figure 24-27 visualize the rapid collapse of Site A. In the middle of the photo from Sollid and Sørbel (1998), figure 24 a break edge is visible. Adjacent is a slide edge with cracks with wool grass growing right below the slope, which indicates relatively stable conditions. The pond had more than doubled in 2006 and the wool grass had disappeared. The break edge had extended. From 2006 the break-down progressed fast, especially in the middle part where the surface was lowered and full of fissures by autumn 2007 (Fig. 26). Large pieces had broken off from the front; the biggest of them measured about 80 cm in width. Most of the cracks along the slide edges were wider than in 2006. In summer 2008 the entire middle part of the land bridge, which in 2006 was about 5-7 m wide, and about 1.4 m height had totally collapsed (Fig. 27). The southern branch showed big cracks in all three years since 2006 but never had any signs of rapid block erosion. It slowly sunk down to its present height.

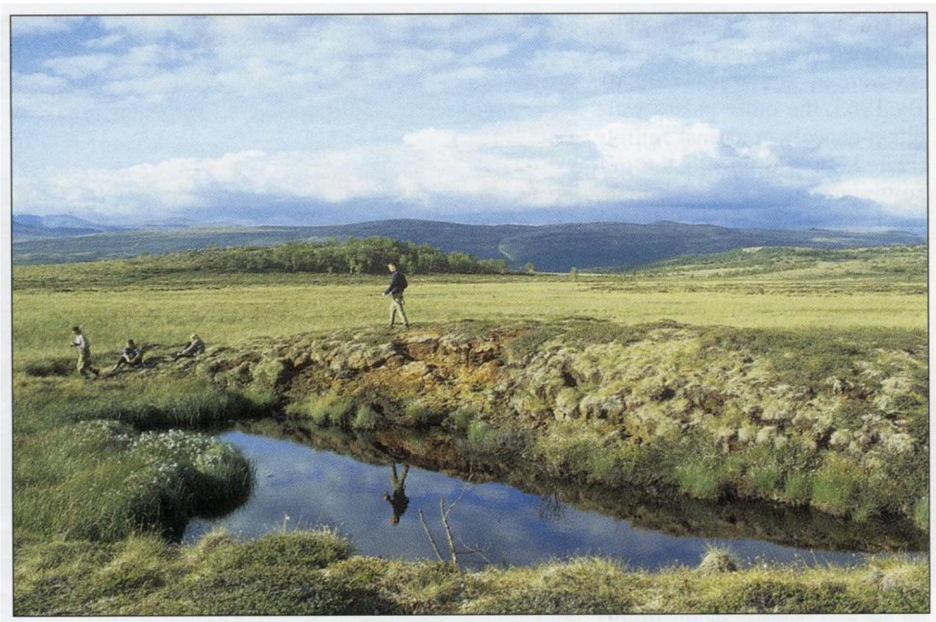


Figure 24 The south-west side of Site A. Photo from 1995 (Sollid and Sørbel 1998, Photo: Leif Sørbel).

Figure 25 A. The south west side of Site A. B. The ridge towards north. Photos from 2006. (Photos: Leif Sørbel).

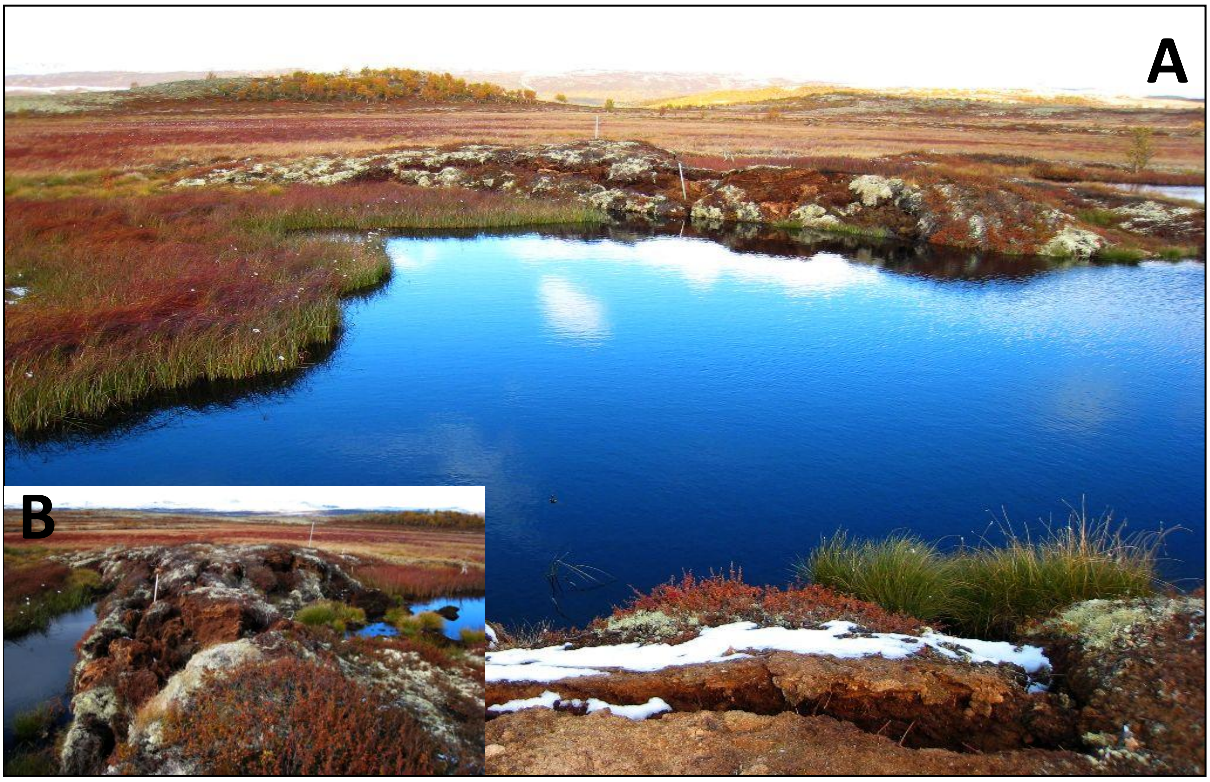


Figure 26 A. The south west side of Site A. B. The ridge towards north. Photos from 2007.

Figure 27 A. The south west side of Site A. B. The ridge towards north. Photos from 2008.

The south-facing edge of Site B has a similar fast erosion speed. A distinct top edge was documented in 2006, with only a few blocks lying in the water below. Since then several blocks with an estimated width of together 1.5 m fell off. The horizontal distance from the edge to the water was about 3 m in 2008 due to dissolving peat blocks. New cracks were already visible behind the edge on the palsa surface. The north-facing edge from Site B was mainly a break edge and exposed to intensive block erosion. Since 2006 several blocks, the largest of several meters in length and at least 1.3 m width, broke off. This huge block basically kept its shape and most of it stuck out of the water in summer 2008.

Wind erosion

The surface of the southeast-facing slopes is exposed to wind erosion in conjunction with the dominant wind direction. There is a complete lack of vegetation and the barren peat layer is exposed. During the field visits in summer, the erosion spots mostly were wet and had a rather uneven surface, in contrast to a very smooth and dry surface during the winter visit in November 2006. In February 2007 the spots very covered by a shallow layer of snow.

Water bodies

Water bodies had already established before the 1960s and in the 1963 aerial photograph several ponds are visible. Four of them, however, continuously increased in size, while the others became smaller or even disappeared due to invading vegetation.

Pond A (Fig. 28), which is largest, lengthens from about 31 m in 1963 to about 42 m in 2006. Its extension tripled in the time span from 1963-2002. It first expanded mainly in length, incorporated a small pond on its way, and so grew southeastwards. In 2008 it nearly had gathered with Pond B. This pond decupled in area from about 26 m^2 in 1963 to estimated 280 m^2 in 2008. It first extended about 15 m eastwards but since 1992 this process had stopped and as demonstrated by subsequent aerial photographs and the field data it widened ever since. Wool grass growing on its eastern water edge indicates stable conditions. Rush is dominant on the western side, and colonisation of the water body from this side is likely. In 2008 a connection had been established between this pond and the southern pond (Pond B and D in Fig. 28).

Both ponds which are situated below the southern edge of Site B (Pond D and F in Fig. 28) did not exist in 1963 but most likely developed from a palsa lagg sometime after that. Since 1979, their area multiplied and erosion processes and back growing vegetation caused a movement towards northeast. The other ponds shown in figure 28 became smaller and got vegetated. While the other lakes are on the same level as the mire, the depression in the middle of the palsa (Pond C in Fig. 28) is situated 10-25 cm above and is identified as palsa göl. The 1979 and 1992 aerial photographs suggest that it was – at least from time to time – water-filled. It was soaked during the summers 2006, 2007 and 2008 and peat and grass were growing in it. While there was no open water registered in 2007, in 2008 water had accumulated along its southern side.

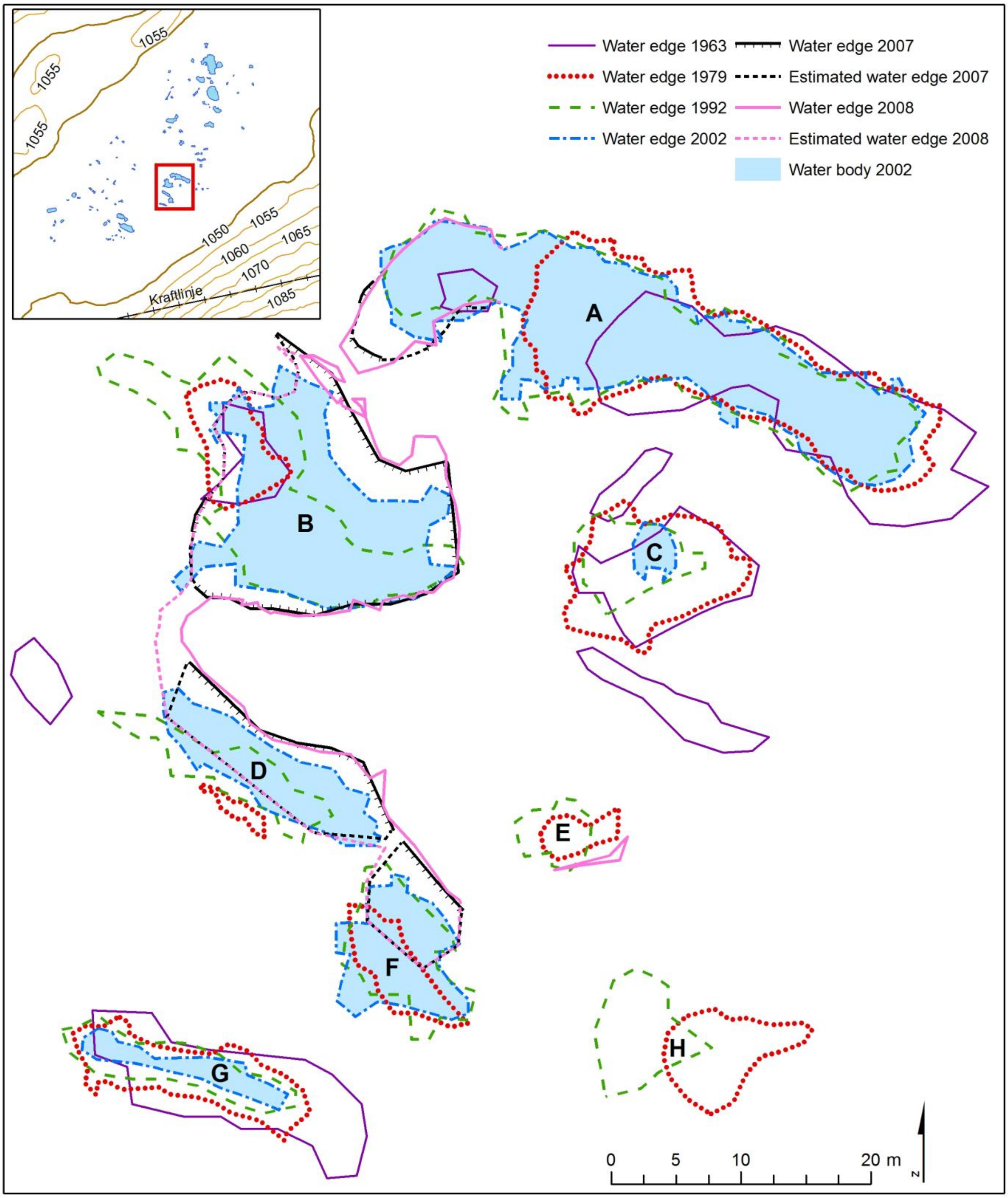


Figure 28 The water lines, based on the aerial photographs. The 1963 and 1979 lines are considered to contain a position error towards the east.

5.2.1.3 Volume loss

During the investigation period from 2006-2008 the investigated palsa lost volume substantially. This occurred not only because of lateral erosion, but also due to a lowering of the surface. In 1976, the palsa almost reached a height of 3 m. The eastern erosion edge was described as 1.8 m high (Jelmert 1978), which is now not even reached by the highest tops. The following profiles display the loss from 2006-2008. The profiles A-A7 (Fig. 29, 30) show the height changes of Site A, which already got described in the text earlier. The heights of the northernmost part of this site decreased slightly. The depression in the 2008 surface is caused by a measurement point which was situated in the bottom of a crack and the "actual" surface was some decimetres higher. However, the point at about 13 m in the longitudinal profile A is a top point and situated more than 20 cm under the 2006 surface. The loss in the middle part is evident and a reduction of about 1-1.2 m in height is recorded within two years. The southern remnant declined by about 40 cm. Profile A4 was taken in 2006 but in 2007 and 2008 too few measurement points existed along this profile and therefore, the profiles A3 and A5 were created.

Site B is plotted on the profiles B and C, which are displayed in paragraph 5.2.3.4 Frozen ground surface. In profile C, a backward retreat of the slope can be observed which can not only be explained by measuring errors. The height difference of Site B in Profile B is mainly due to an error in the terrain model and could not be confirmed by observations in the field.

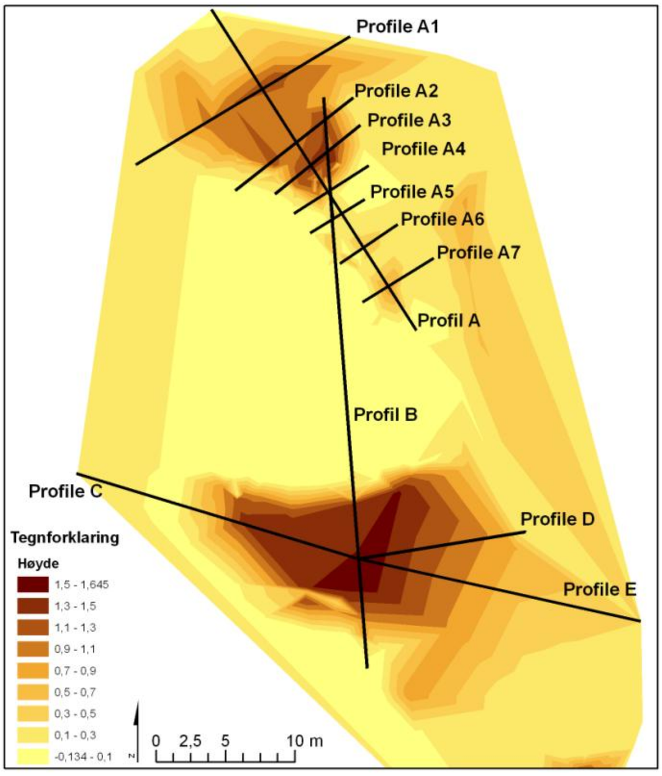


Figure 29 An overview over the position of the profiles. The profiles were taken from N-S and SE-NW, respectively. The terrain model is from 2008.

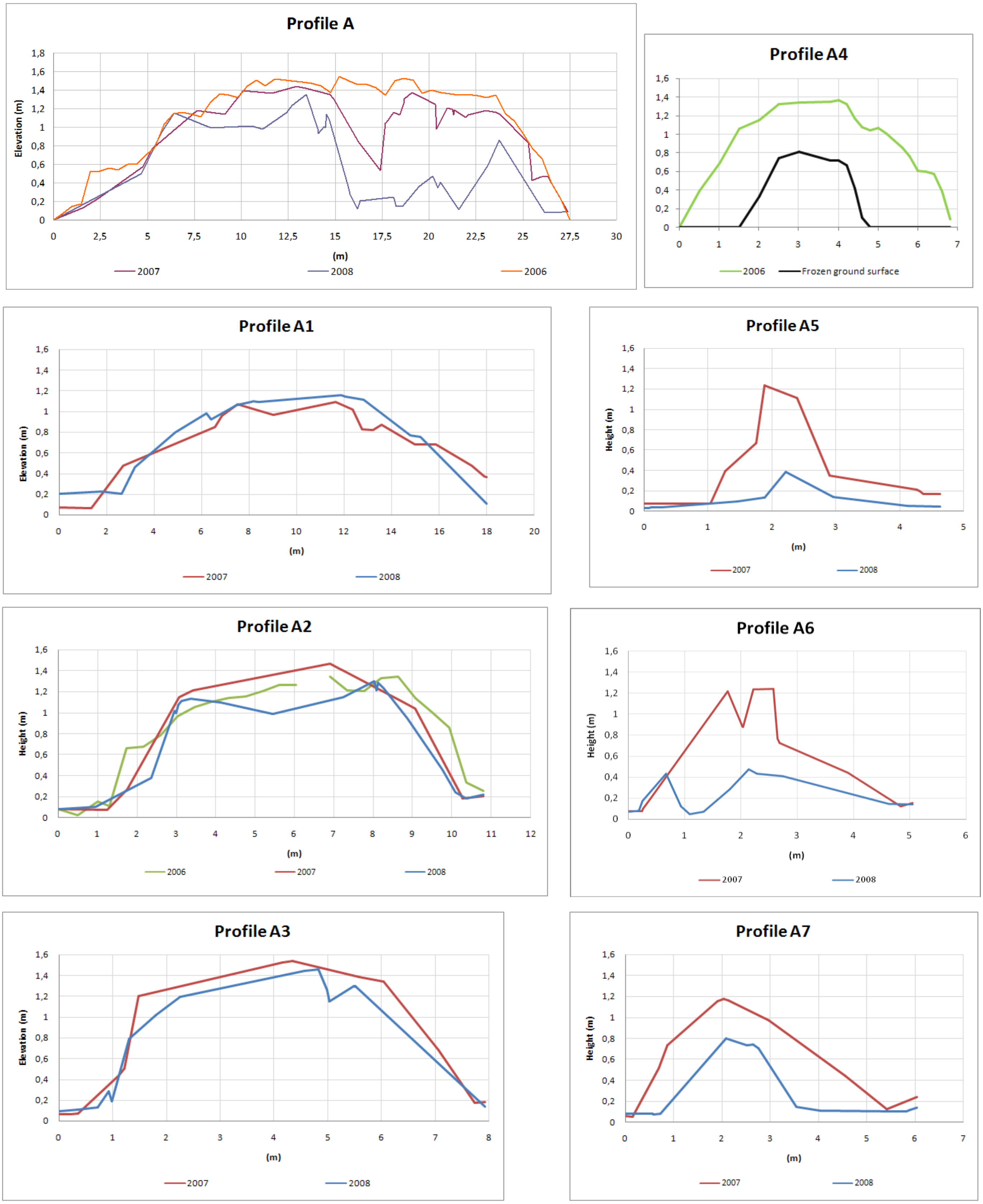


Figure 30 Height profiles from 2006, 2007 and 2008. The profiles were taken from N–S and from SE–NW respectively (see Fig. 28 for location of profiles).

5.2.2 Field measurements

5.2.2.1 Data logger temperature during the observation period

Especially in winter, the air temperature at the palsa site is lower than at Fokstua station, sometimes up to a few degrees (Fig. 31). In summer, the temperatures are similar, with the Fokstua temperature usually being slightly higher. For 2007, the MAAT was calculated from the daily means for the palsa site and Fokstua with the result that the MAAT for this specific year was 0.23°C lower at the investigated palsa than at the weather station. The difference between the surface temperature and the air temperature is significant in both winters, but relatively small during the warm periods. The temperatures in the palsa reflect a smoother pattern.

Obviously, the range of the daily temperatures is reduced the further down the sensor is positioned. The sensor at 70 cm depth did not work properly, which can be recognised by the turbulent up and downs above zero degree during winter 2006 or autumn 2007. The peak in mid August 2007 is also too steep and immediate for being correct. Only February and March 2008 seem to have usable values which can be deduced from the way it corresponds with the temperature from 30 cm depth.

The changes of the air temperature is delayed longer the lower you get. This is valid for both rise and decline. This offset is visible e.g. during spring 2007. The surface temperature rises rapidly first, stays just below 0°C for a couple of weeks and jumps above zero at the end of April. The temperature at 10 cm and 30 cm depth rise simultaneously with the surface temperature but when they reach a temperature of marginally below 0°C they remain at this level. This pattern is observed during all transition periods. The response time for the 10 cm depth is nearly two month. At 30 cm depth further 1.5 month are necessary to adapt to the temperature change on the surface. The response time of the 10 cm depth in autumn 2006 was short, while the temperature at 30 cm depth required about 2.5 month to decrease substantially. In autumn 2007 and spring 2008 a relatively even offset of between one and 1.5 month can be noticed.

The temperature at 70 cm depth at the end of the winter season in 2008 was not lower than -3°C.

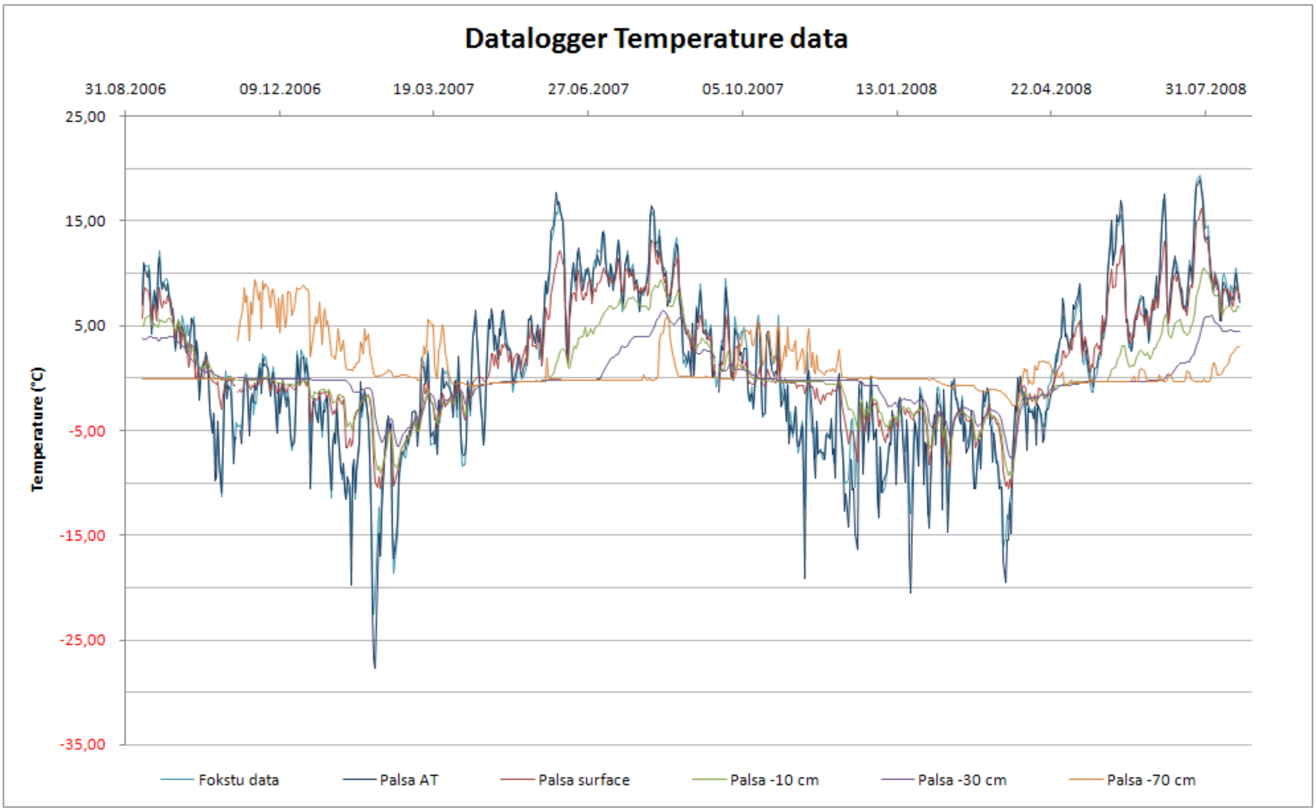


Figure 31 Mean daily temperatures during the observation period from 11.9.2006-22.8.2008. The temperature in 70 cm depth is considered to show wrong values apart from February-Mars 2008.

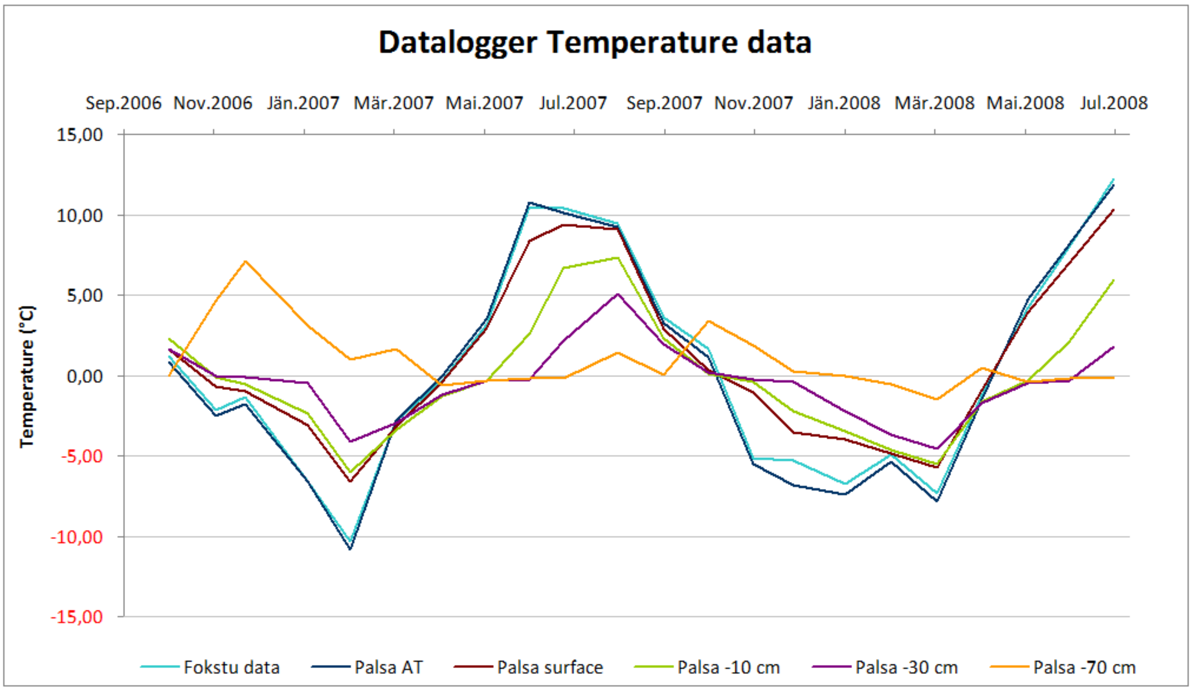


Figure 32 Mean monthly temperatures from Oct. 2006-July 2008. The temperature in 70 cm depth is considered to show wrong values apart from February-Mars 2008.

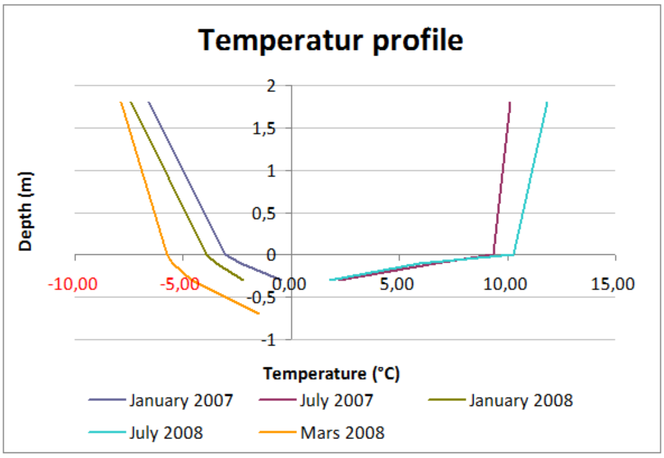


Figure 33 Average temperature for January 2007, 2008 and July 2007, 2008 and Mars 2008.

For the temperature profile (Fig. 33), the average for January and July were chosen. March 2008 is the only month with temperatures available for the 70 cm depth and therefore Mars is displayed as well. Although the air temperature at the site is not considerably lower than in January of the same year, the surface temperature is more than 2°C lower. This is also valid for the temperature at 30 cm depth. Apart from the generally lower temperatures in January 2008, the January curves are similar in both years. The July temperatures are very much alike in the ground, but the surface- and the air temperature in July 2008 are somewhat higher. In late winter, cold air had longer time to penetrate into the ground and this time delay is visualised with the temperature curve for Mars 2008.

5.2.2.2 Temperature from 1865-2008

Based on regression analyses, the temperature data for Fokstua and Dombås respectively were used to prolong the data from the palsa site back in time. The overlapping time span is very short and although the correlation is relatively high for this period, you may rest assured with inaccuracies. The regression analysis is also based on the assumption that the palsa temperature has been non-affected by palsa development. The correlation becomes poorer the deeper the temperature was measured. The -30 cm temperature correlation was considered as too weak and is therefore not plotted on figure 34. All regression analyses can be found in Appendix E on the Appendix-CD.

The backwards calculation gives an overview over the temperature development over the last 143 years. The general picture shows that all temperatures rose to a certain degree. However, the trend curve for the MAAT at the palsa site is steepest and displays an increase from about -1.7°C to just above 0°C. During the entire period the temperatures from Fokstua are situated above the ones measured at the palsa site but an alignment towards 2008 is recorded. The Fokstua temperature increased by about 1.7°C. The trend curve for the temperatures measured in 10 cm depth is flattest and rises only by about 0.8°C. The palsa surface temperature increases by about 1.5°C.

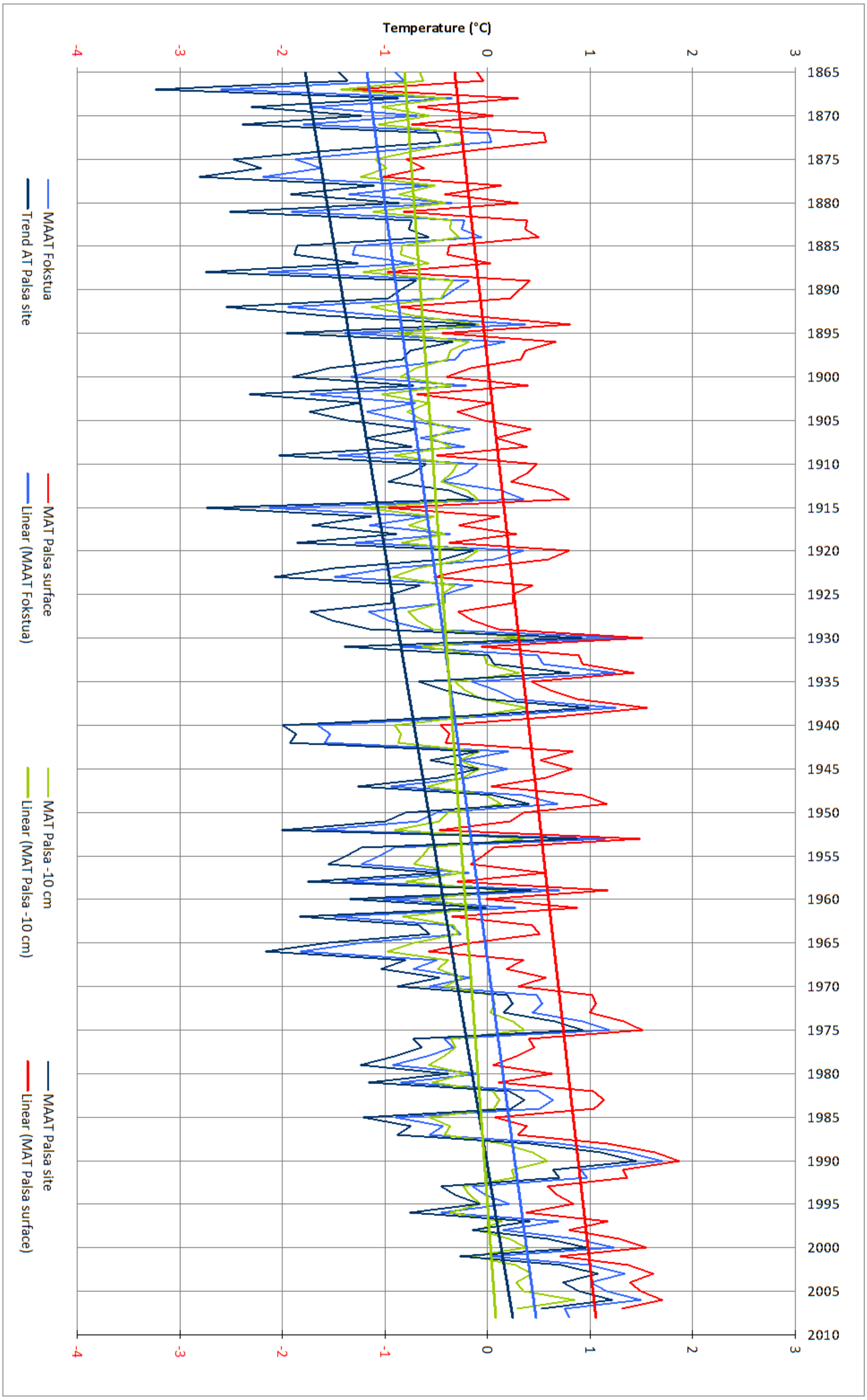


Figure 34 MAAT of Fokstua and the Palsa site, the surface temperature and the temperature in 10 cm depth from 1865-2008.

As already described above, both air temperatures have a higher range than the surface temperature. The subsurface temperature at -10 cm is smoothest. All temperatures increase slightly until 1930. The warm period during the 1930s is reflected in all locations. During the cooler period from the 1940s to the 1960s the 10 cm depth temperature does not change notable and remain pretty much at the same level. The air temperatures express a decrease in that period. The warming since the mid 1960s affects all positions and a dramatic temperature rise is noticed. Two peaks emerge, one during the 1970s and another around 1990. Since 1990 all temperatures stayed above zero with only a few exceptions.

5.2.2.3 Snow distribution

Snow depth was measured along the profiles B, C, D and E (see Fig. 29 for positioning). In 2006 the mire was covered by a 20-30 cm thick layer of snow but with a very uneven distribution around the palsas. The water of the mire was unfrozen beneath the snow. The tops of the palsas were nearly blown free from snow and largely only a few centimetres of snow were detained by the vegetation. The bare surface was exposed on some top spots. On all sides wind drift had accumulated snow masses which are also represented by the snow profiles. During the fieldwork period in November 2006 southwesterly winds dominated but at the field visit in February 2007 it was calm.

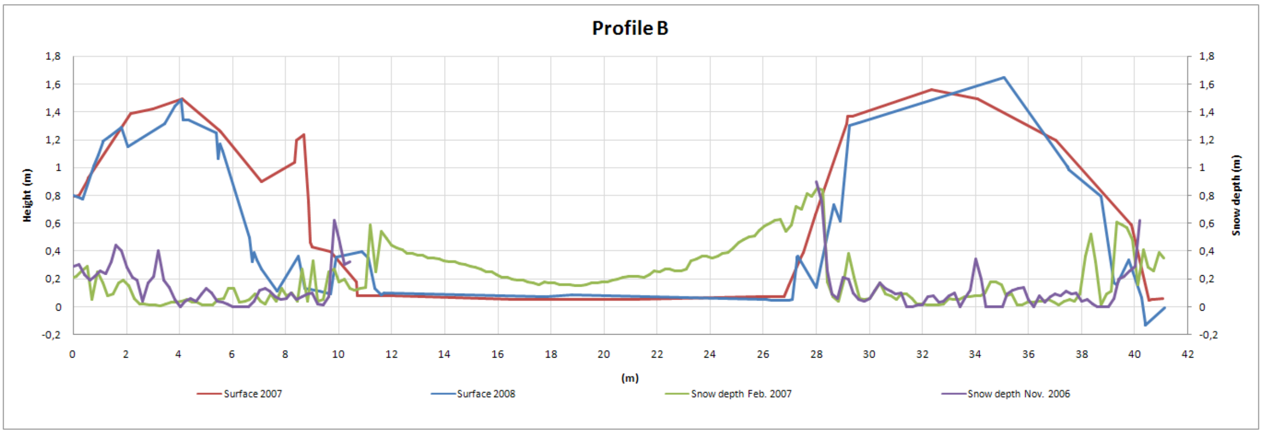


Figure 35 Surface of 2007 and 2008 and snow depth during 2007 along the Profil B.

On profile B, which shows Site A on the left hand side and Site B on the right hand side, higher snow depth is mapped towards the edges during both winter field visits. There was more snow on the northern slope of Site B than on the south-facing slopes. This can be explained by the dominant wind direction from the south. Due to safety aspects, the snow depth on the pond was only measured in February. Then it had a minimum depth of 20 cm.

Profile C (Fig.36), D (Fig. 37) and E display also a shallow snow cover on the top of the exposed convex forms and growing accumulation towards the sides. Profile E can be found in Appendix F on the Appendix-CD.

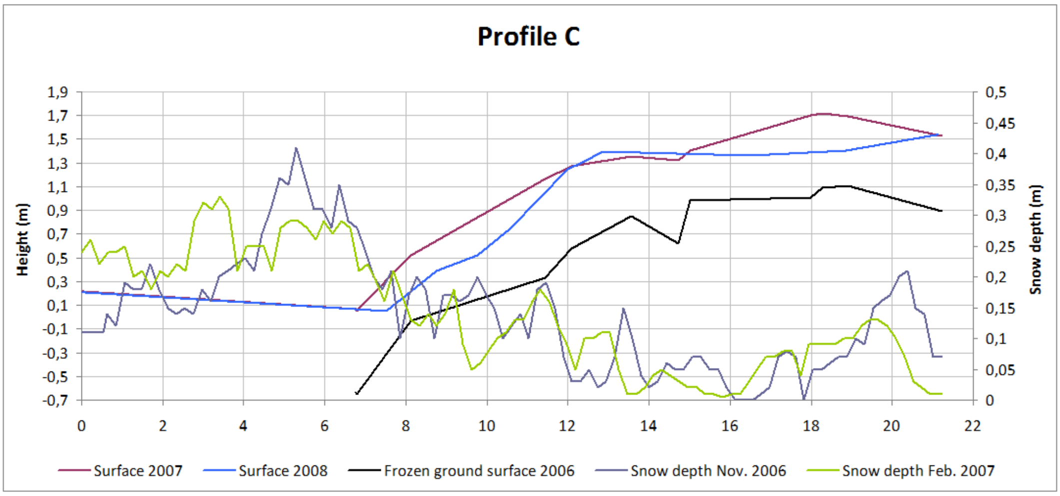


Figure 36 Surface in 2007 and 2008, depth of frozen ground surface 2006 and snow depth during the winter 2006/07.

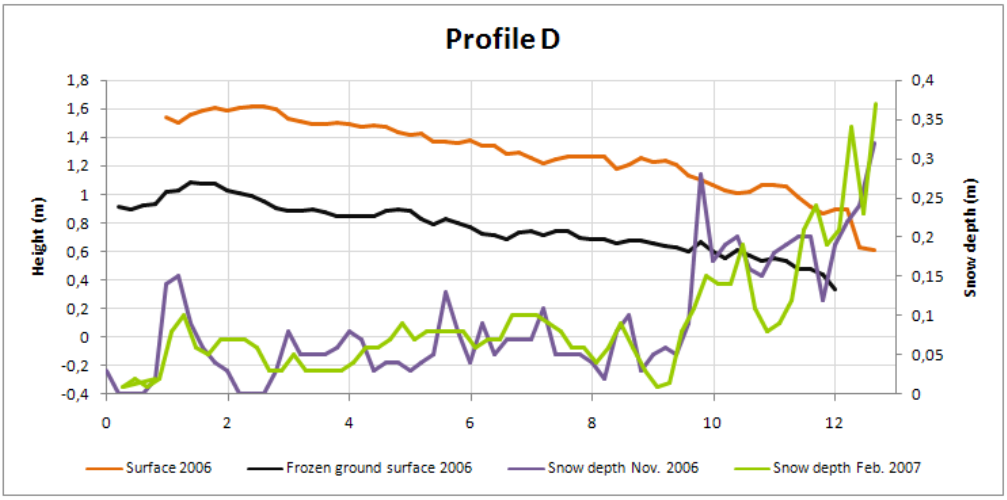


Figure 37 Surface in 2006, depth of frozen ground surface and snow depth during winter 2006/07.

The snow distribution was similar during both winter visits (Fig. 38). It was snowing about one week prior to the visit in autumn 2007 and snow could still be found in the shadow on the north- and northeast-facing slopes as well as in gaps and cracks (Fig. 22).

Figure 38 Snow distribution in November 2006. The photo is taken from the same spot as the cover figure.

5.2.3.4 Frozen ground surface

The depth of the frost body was measured at the beginning of September in 2006 when the seasonal thawing layer is nearly on its thickest. Seppälä (1982b, 1983) suggests measuring the depth to the frost table in late October or beginning of November since heat penetrates slowly into the peat. Melting decelerates towards the end of the thawing season, and the difference probably is not very great, therefore, it is assumed that the frozen ground surface from this survey is synonymous with the permafrost table.

Profile A (Fig. 39) displays Site A with the surface height of 2006, 2007 and 2008. The frozen ground surface mainly follows the 2006 contour but its depth is doubled on the top compared to the sides. Two years later only in the northernmost and the southernmost parts frozen ground was observed. On the northern slope was the depth between 35-45 cm and about 50 cm below the remaining top. The southern part still contained frozen ground in a depth of 60 cm on its top and about 80 cm on the side. To display the depth of the frozen ground for Profile C (Fig. 36), the surface of 2007 was used for visualisation since the measurements of the 2006 survey were insufficient. Both in Profile C and D the frozen ground becomes shallower towards the edges. There was approximately the same thawing rate on the east- and west-facing slopes.

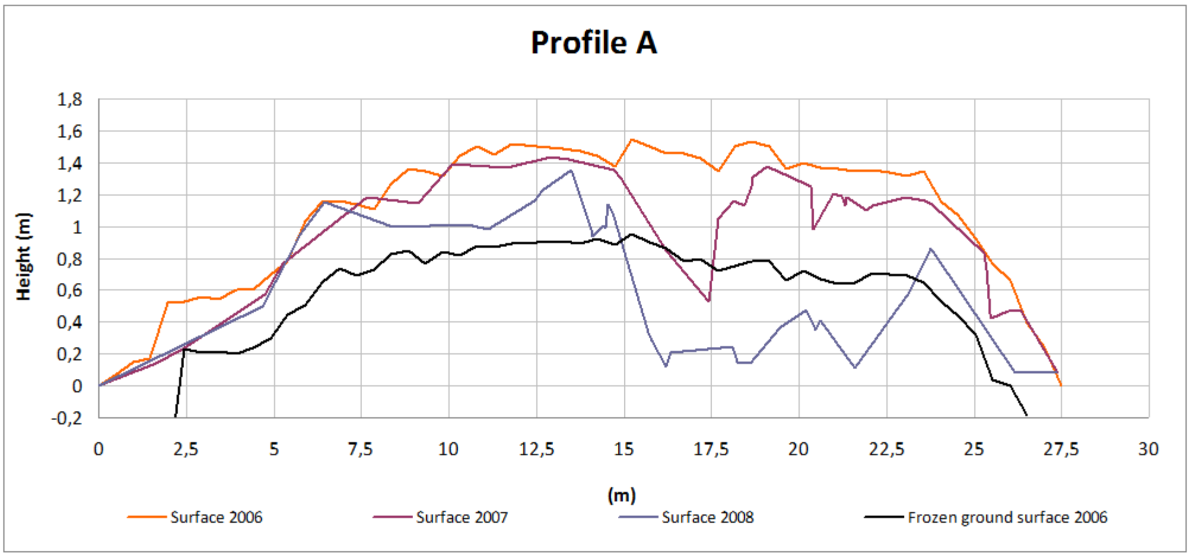


Figure 39 Profile A, showing the surface in 2006, 2007 and 2008 and the frozen ground surface in 2006.

5.2.2.4 Soil and subsoil composition

On Site A the underlying mineral material was observed along the erosional sides. The mineral layer was covered by approximately 80 cm of peat and their transition zone was relatively sharp. More than 90% of the material consists of clay (8.5%) and silt (85%) as displayed by Fig. 40. After removing unfrozen material from the north-facing slope of Site B mineral material was observed in 2006 although it was never as exposed as on the southernmost edges of Site A. No mineral material was excavated in the pit (about 75 cm depth) on top of Site B where the data loggers were installed in the same year. When a small trench (for positioning see Fig. 17) was dug a few meters east of Site A in 2006 the frozen ground surface consisting of frozen peat and ice lenses of several millimetres in thickness were found.

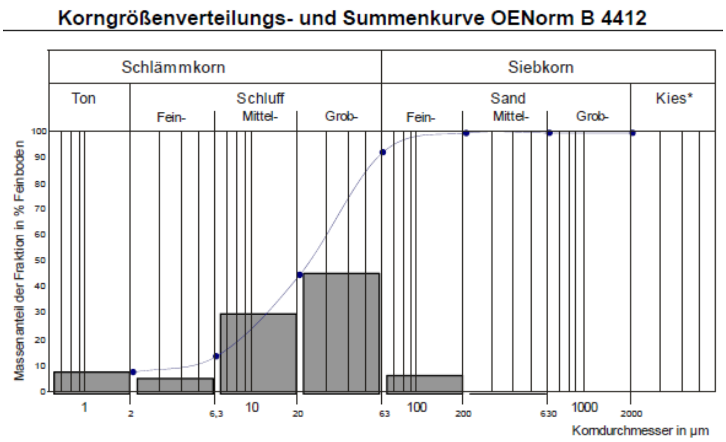


Figure 40 Grain size analyses of the exposed mineral material on Site A.

6 Discussion

6.1 Why does the investigated palsa break down so rapidly?

Block erosion and thermokarst, ground water level, wind erosion and soil and subsoil composition are factors which influence the break-down of the palsa to a certain extent. The degree of their influence will be discussed below.

6.1.1 Intense erosion processes

Cracks generally occur already in the embryo palsa but are small and have distinct edges. Svensson (1962) suggests that the cracks develop due to ice cracking and due to drying of the lifted peat surface. Through rising of the surface the cracks become wider and Åhman (1977) noticed deep cracks distributed over the entire palsa summit. The investigated palsa only showed cracks along the edges and slightly inwards but not on the top. In autumn 2007 snow from an early snow fall was still apparent in the cracks. Obviously, the snow got accumulated there and – sheltered from direct solar radiation – survived an entire week with temperatures above zero. This observation may reflect a typical autumns/spring condition with sheltered snow accumulations in the cracks leading to a steady penetration of melt water downwards. This enhances further thawing of the frozen ground.

After the establishment of cracks and water accumulations along the foot of the palsa, intensive erosion processes are initiated. Thermokarst- and block erosion processes accompany each other. The crucial factor is the different heat absorption of soil and water (Svensson 1969, Harris 2002) with water having a several times higher heat capacity. After the palsa is surrounded by water bodies, the degradation accelerates and the decay is rapid. Vegetation has no chance to establish or survive because the erosion is simply too fast. Zuidhoff (2002) documented the total collapse of a palsa within four years in Laivadalen, Northern Sweden, after ponds already had developed around it. The investigated palsa at Haukskardsmyra showed a similar picture. This indicates that the rate of erosion multiplies in the degradation stage of a palsa.

Excursus – clarification of terms:

Block erosion is a widespread term and is used by most authors who describe palsa degradation (e.g. Svensson 1962, Åhman 1977, Seppälä 2003). However, when this process is described, different interpretations arise. E.g. Svensson (1962), Wramner (1967, 1973), Åhman (1977) assume block erosion to be the active break off of peat blocks while e.g. Seppälä (2003) uses the term block erosion also to describe the down sliding of peat blocks on the frozen core surface.

In this thesis, block erosion is divided into a high motion process along a break edge and a slow motion process along a slide edge as described in paragraph 5.2.1.2 Erosion processes.

As discussed by Åhman (1977) erosion from the side is likely to be initiated by a palsa lagg and is dominated by a down sliding process in the starting phase.

From detailed studies of the lateral erosion processes during my field work, I assume that a steep break edges may develop after a while and the low horizontal distance between the water and the edge causes additional stress in the erosional edges' upper part. Already existing cracks widen and peat blocks start falling off and come to lie on their side on the food of the edge. After the break off, this process seems to pause for a certain time which may have several reasons. The undissolved peat pieces lie in the margin of the pond and in this way increase the distance from the edge to the water body. Hence, the heat discharge towards the edge and subsequently the thawing of the frozen ground is reduced. Furthermore, most of the loose material broke off and new cracks and fissures have to develop again on the upper edge. However, the time span which is needed to create these weak zones seems to vary. Along the steep break edges, new cracks had nearly simultaneously developed after big break offs.

Such break edges did only exist in the higher parts of the erosional edges. Towards the margins, when the palsa becomes lower slow slide processes seem to be dominant. The main reason for the development of slide edges seems to be gentler slopes. These areas are characterised by a slow lowering of the palsa surface which causes the peat on the slopes to get waterlogged. First, this makes the peat heavier and, together with the frost horizon acting as a glide surface, peat mats slowly creep towards the water. Secondly, the higher heat conductivity due to the presence of the water proceeds melting of the frozen core. A slow advance of the water line can be noticed, since the sunken peaty material immediately disappears under the water surface.

As I know these processes have so far only been referred to as block erosion, while in my point of view two different processes, "block-slide erosion" – a relatively slow down gliding movement of peat blocks and "block-fall erosion" – a relatively fast break off of peat blocks, can be distinguished.

On none of the edges on Location 4, a tilting of the entire peat block by 180° as described by Åhman (1977, see Fig. 16 in paragraph 3) could be noticed. The observed sites were of a height of maximum 1.5 m and it is likely that a higher edge is needed in order to tilt a block completely. Since Åhman also mentioned a "down ward creeping", which indicates that the slope(s) he is describing must be gentler, I conclude that his process must occur in the initial phase of side erosion.

Degradation of a palsa is, just as the rising above the surface of a mire, a part of its cyclic evolution (see Fig. 15 in paragraph 3). Once a break edge has developed, a positive feedback sets in and there is virtually no stop until the entire feature is melted. Rapid erosion of palsas has also been reported from other palsa bogs such as near Haugtjørnin, Dovrefjell (Sollid and Sørbel 1998) or from Laivadalen, Northern Sweden (Zuidhoff 2002).

6.1.2 Ground water level

Thorhallsdottir (1994) studied the development of a palsa bog which partly got flooded by a newly dammed lake in Iceland. The investigations showed that the availability of ground water is necessary to allow palsa growth but at the same time can act constricting when water level rises too high. However, the water level at the investigated bog increased by only 5-10 cm from 2006-2008, while Thorhallsdottir reports a rise of at least half a meter.

In the Haukskardsmyra palsa bog, the narrow passage between the ponds B and D (see Fig. 28 for positioning) was dry and underlain by frozen ground in 2006, but in 2008 was situated under the water surface. Still living vegetation indicates either a fast rise of the water table or a sinking ground surface. A water table increase by 5-10 cm might have contributed to further melt down by narrowing the girth of the frozen core. The surface will subsidise at the same time the ice melts. The rise of the water level can be explained by high precipitation in the period before the field visits and is assumed to be part of the natural fluctuation of the water level.

6.1.3 Wind erosion

Deep wind erosion of peat surfaces are reported by e.g. Åhman (1977), Zuidhoff (2002) and Seppälä (2003). Åhman (1977) reports surface erosion due to winter wind of about 50 cm within one year from Northern Norway. 20 - 40 cm deep erosion is observed by Seppälä (2003) in the Lake Ahkojavri area, Finnish Lapland. The rate of abrasion is unknown. Seppälä (2003) concludes that even the absence of cracks on the surface can be explained by either wind erosion or by peat which got redeposited in them. In Laivadalen, Northern Sweden a lowering of the surface by all in all 80 cm was inferred by Zuidhoff (2002).

In the Haukskardsmyra palsa bog, the erosion scars created by wind erosion on Location 4 are surrounded by intact vegetation and are not very large. In the observation period from 2006 to 2008 no perceptible changes of the abrasion surface were noticed. During the field visits in the summers the peat surface was mostly wet and in the winter 2007 the summit of the palsa was covered with a few centimetres of snow. Wind speed in the Dovre area is highest in the winter season and seem to be able to erode wind exposed fibrous peat surfaces. In summer, wind speed is somewhat lower and especially when the surface is moist and the peat heavy, wind erosion is assumed to be marginal. However, wind erosion may be a determining factor in regions with very high wind velocity, but it seems not to be the main agent for the break-down of the palsa at Location 4. Though, it may influence the depth of the seasonal thawing layer due to the different surface properties.

6.1.4 Snow- and frozen ground depth

Snow is an effective insulator and may inhibit frost penetrating into the ground (Seppälä 1990). Due to the undulating surface of the mire, the depth of the snow cover varies greatly. The sides of palsas are typically covered by redeposited snow which got accumulated due to wind drift. The thick snow layer prevents frost from penetrating deeply into the ground and in spring, melt water thaws the shallow frost layer after the snow has melted (Seppälä 1990). The top summits, which first become snow free, and thus exposed to radiation, have a deeper seasonal thawing layer (Seppälä 1976, 1983). Seppälä (1976) reported strong asymmetrical melting due to radiation from the south of a palsa located in Enontekiö, Northern Finland, while rain caused a more even melting.

As shown in the profiles A, C and D (see Fig. 36, 37 and 39 in paragraph 5), the seasonal thawing layer of the investigated palsa in Haukskardsmyra is shallower towards the slopes, which reflects the observation by Seppälä. The higher thawing rates on south-facing slopes as observed by (Seppälä 1976) can not be reconstructed. Only the east- and west-facing slopes can be taken into account (since profile B along Site A was influenced by lateral erosion) where the rates were approximately similar.

6.1.5 Soil and subsoil composition

Many authors have pointed out the effect of mineral material situated under the surface peat layer (e.g. Åhman 1977, Wramner 1973 and Zuidhoff 2002). When the active layer deepens and the silty substrate becomes a part of it, thawing can proceed much faster due to the much higher thermal conductivity compared to dry peat. Thus, block erosion processes on the side accelerate (Åhman 1977). The collapse of a mineral-cored palsa is documented from Laivadalen, Northern Sweden (Zuidhoff 2002), where the mineral subsoil was found at 70 cm depth. The active layer did not reach down to the mineral soil, but cracks in the palsa surface reached down to the silty subsoil and contributed to the rapid decay (Zuidhoff).

On Location 4 at Haukskardsmyra, the surface of the frozen ground was 60-67 cm below the summit surface and 30-50 cm on the sides (measured on 24th August 2008). During the previous years, the thaw depth was measured later in summer and therefore was slightly deeper. The mineral material was observed on an erosion edge in a depth of 80 cm and it is assumed that the active layer did not reach as far down. On the sides, however, silty material was exposed and heat could easily penetrate. These circumstances may have lead to an increased thawing rate.

6.2 The cyclic evolution of a palsa

Several cases where both – decay and regeneration of palsas – appears side by side at the same time without indication of a climatic change are documented. In western Utsjoki, Finnish Lapland palsas in all stages occur. Mature, old and collapsing palsas, rim ridge remnants as well as young and recently formed palsas can be found in one location (Seppäla 2003). Wramner (1973), who investigated palsa mires in Taavavuoma, Swedish Lapland describes that degeneration or regeneration dominates in different mires, but all together approximately balances each other.

In the nearby area of the investigated mire, in a bog close to Haugtjørnin small embryo palsas were observed by Sollid and Sørbel (1974, 1998) in 1972. Also during a field visit in 2006 small embryonic domes were situated in the bog. Similar features were identified in Haukskardsmyra (Jelmert 1978, Lie 1996). These temporarily small frost mounds seem to form occasionally under a few consecutive cold winters conditions with little snow and disappear after a few years (Seppälä 1990, Sollid and Sørbel 1998, Zuidhoff and Kolstrup 2000). Therefore, they seem to be an indicator of recent climate conditions. However, none of these features in the study area seem to survive longer than several years and generally the mire shows a degrading trend.

6.3 The relation of the investigated palsa to climate – Temperature- and precipitation rise during the last century

According to Lundqvist (1951), palsas in Sweden require at least 120 days with temperature below -10°C and a winter precipitation (from November to April) of less than 150 mm. Åhman (1977) approves Lundqvists temperature prerequisites to be valid for palsa occurrences in Finnmark. Åhman documents pals bogs located in areas with a MAAT between -1° to 0°C and a mean annual precipitation below 400 mm or less than 100 mm from December to March. Ruuhijärvi (1960 in Åhman 1977) suggests that the most distinct palsas can be found in continental climate with an MAAT below -1°C. Rapp (1982) reports from palsa bogs in the Kiruna-Abisko region which are situated in areas with thin snow cover and a MAAT of roughly below -1°C. In Finnish Lapland, Salmi (1970) concludes the southern limit to coincide with the -1°C isotherm and the 400 mm isohyet for annual precipitation. Lundqvist (1962) assumes that palsas occur in an area with a temperature below 0°C for more than 210 days or a MAAT of -2° to -3°C. Both summer- and winter precipitation are of importance. Summers need to be dry and winter precipitation from November to April must not exceed 300 mm (or 50 mm per winter month). Luoto (2004) calculated that a MAAT of -3° to -5°C and a precipitation of lower than 450 mm provide the optimum conditions for palsa mires.

The meteorological weather station at Fokstua had an average MAAT of -0.8°C in the period 1901-1930, -0.5°C 1931-1960 and 0.0°C 1961-1990. The average annual precipitation 1931-1960 was 439 mm (Sollid and Sørbel 1974, 1998). Due to the higher altitude of the palsa bog, Sollid and Sørbel (1974) concluded the air temperature to be lower at Haukskardsmyra.

However, it is questionable if the present climatic conditions are sufficient for the palsa survival at Haukskardsmyra and also in Dovre in general.

Figure 41 shows the backwards calculated MAAT for the palsa site and Fokstua. A warming trend is evident and it also illustrates that the average MAAT at the palsa site has mainly been above 0°C since the mid1960s in contrast to average temperatures below -1°C at the end of the 19th century. The rise of the MAAT is mostly due to warmer winters rather than due to higher temperatures in summer, which probably leads to less deep frost penetration in the winter months. All graphs displaying regression analyses and monthly MAAT from 1923-2008 can be found in Appendix E and A on the Appendix-CD.

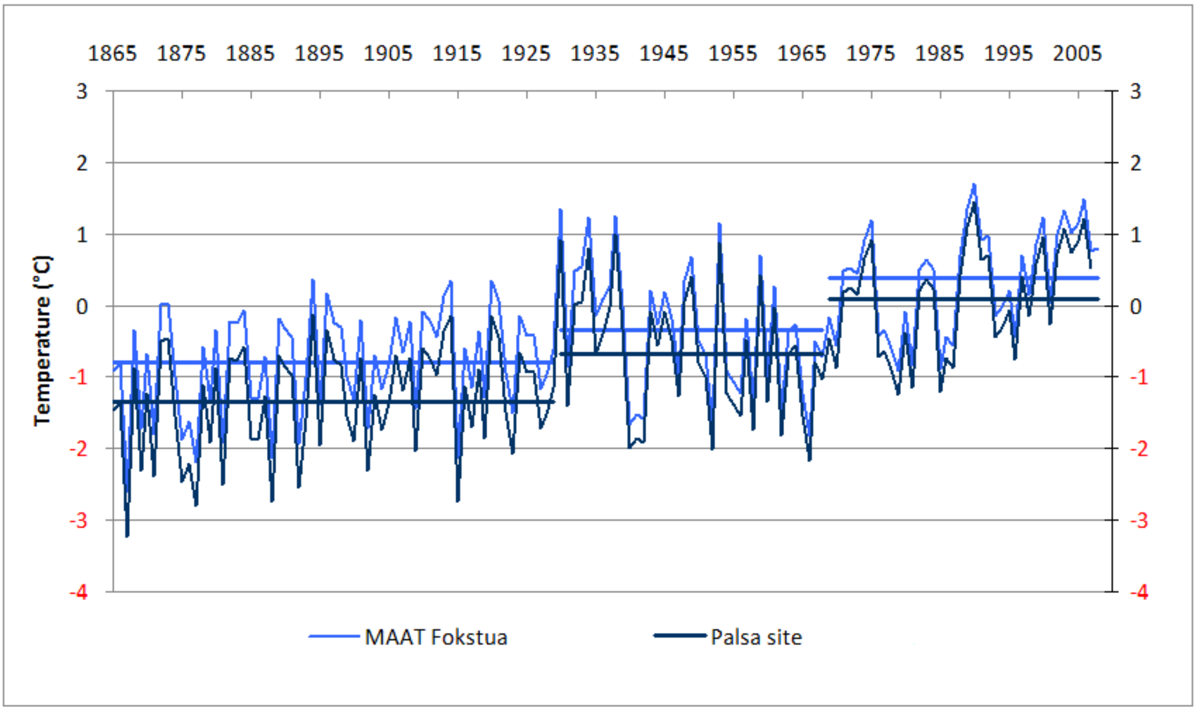


Figure 41 The Figure shows the MAAT at Fokstua and the palsa site. The horisontal line displays the average MAAT for 1865-1929, 1939-1968 and 1969-2008 for Fokstua (light blue) and the palsa site (dark blue).

Precipitation is the second relevant climatic factor for this palsa bog. The average precipitation from November to April during the last 10 years was about 160 mm and therefore lies within the 300 mm range set by Lundqvist (1962) and also stays below 50 mm per winter month. Lundqvist's (1951) limit of 150 mm from November to April is slightly exceeded, though. Precipitation from December to March is about 130 mm whereas the maximum limit for this period which was set by Åhman's (1977) is 100 mm. The calculated average annual precipitation 1923-2008 is 450 mm, whereas it shows an increasing trend towards today. However, the 400 mm limit, which is set by Salmi (1970) and Åhman (1977) is exceeded for most of the period. Nihlen (2000) and Seppälä (1988b) consider summer precipitation as an important limiting factor because of the decline of the insulating capacity of the peat layer and increased ground warming. The average precipitation at Fokstua for the last 10 years from May to October is about 300 mm.

I assume that Lundqvist's (1962) and Luoto et al.'s (2004) relatively high precipitation values can be compensated by somewhat lower MAATs. This prerequisite is not given at Haukskardsmyra since the bog is now situated in an area with a MAAT just above 0°C and – for a palsa region – relatively high precipitation. Based on the existing meteorological data, Haukskardsmyra does no longer provide a favourable climate for palsas, and it did not do so for at least the last 40 years.

The temperature profile of the palsa site shows that the average temperature in 10 cm depth in January was relatively high in 2007 and 2008. In 2007 it was -1°C which likely can be explained by the warm November and December. However, the temperature in 70 cm depth was as high as -3°C in Mars 2008. This indicates that the depth of zero annual amplitude must be situated somewhere between -3°C and 0°C and the permafrost in the palsa is relatively "warm".

As stated earlier, the aerial photograph from 1963 clearly shows many ponds and pools on the surface and along the sides of all palsas in the mire. Most of them existed on the aerial photograph from 1955 (in Jelmert 1978) - some were already very well developed. Since it takes long time to create such distinct thermokarst ponds, this indicates that degradation of the palsas has already started somewhat before 1955. The palsa at Location 4 does show significant traces of erosion and is separated in two parts in 1963. The picture is similar in 1955. It can be assumed that it took about 50 years (from 1955-2008) to melt the northern part of the palsa. Taking into account that this part was of smaller size than the "missing" - already thawed - part between the two palsa parts in 1955, degradation may have started some 50 years earlier.

In the northern section of the mire, two lakes are particularly striking. Already on the 1955 aerial photograph they are clearly visible (see Fig 19 in paragraph 5). The southerly lake was stable from 1963-1980 (Lie 1996) but is narrower on the 1992 photograph, probably due to advance of vegetation. Circular palsa lakes, which develop on the same spot of a palsa after its degeneration, are reported from e.g. Svensson (1962, 1969), Salmi (1970), Wramner (1973), Åhman (1977) and Seppäla (1982a, 1986). However, the palsa around the southerly water body is not yet completely melted and there is no clear rampart apparent around the lake. It most likely does not indicate the death of another palsa in this section. However, the position of the lake in the middle between the palsas of locations 5 and 6 suggests that the volume of both palsas must have been much larger since it needs an abundant amount of melt water to feed such a big pond. The palsas have probably been connected at a certain time. This hypothesis is supported by observations made by Jelmert (1978) who found a series of small palsas, covered by good established palsa vegetation, north and northeast of complex 5. These might be the "left-overs" of an earlier somewhat greater palsa extension including locations 5 and 6. The mire drains towards north, which suggests that this part is exposed to a slightly higher water level. Thus, this may (have) accelerate(d) melting.

In the more southerly part of the bog, the aerial photographs give the impression that the palsa plateaux of locations 1 and 2 originally were one vast plateau. But in 1955 the areas between them and especially towards the palsa of Location 3 seem to be heavily eroded. Inferring that it needs several tens of years to thaw and level a similar area (as between locations 5 and 6 and between 1 and 2, respectively) it is profoundly questionable that degradation first started during the warm period in the 1930s.

Deduced from the melting rate of a palsa plateau near Haugtjørnin it is assumed to take 40-50 years to melt down a palsa completely (Sollid and Sørbel 1998). This, however, does not appear to be valid for Haukskardsmyra since the palsas there are simply larger which implies that the time span needed to melt a palsa plateau or a dome palsa completely free of permafrost is depending on its dimension.

The results points to that the palsas in the investigated area respond to warmer temperatures during the 20^{th} and supposedly already during the 19^{th} century and that they have not been in equilibrium with local climate for at least 75 years. Melting might have started as early as after the end of the Little Ice Age.

6.4 Is the investigated palsa going to disappear completely?

During the last 3 years, the observed palsa was substantially reduced in extension and height. The sides have undergone intensive erosion and the ponds surrounding the palsa advanced. Its northern part collapsed. The main destructive factor seems to be the various types of block erosion. As discussed, block erosion once started together with the enlargement of the water bodies does not stop until all frozen ground is melted. This process might be amplified by higher winter- and summer precipitation as well as rise of the water level. Degeneration of the palsa can be documented since 1955 and since then no regeneration of that palsa (or parts of it) could be observed. All the described factors points to that the palsa is in its final stage and erosion will continue until the entire permafrost body is melted.

6.5 Is the investigated palsa representative for the entire bog/ Dovre/ Fennoscandia?

Dome palsas, like the palsa at Location 4, have a distinct convex form and are therefore effected by break-down processes to a higher degree than palsa plateaux (Wramner 1983). The latter, such as the big remaining palsas in Haukskardsmyra, have a nearly plain surface and are shallower. This makes them more stable and less vulnerable for erosion. However, the entire bog seems to show great reduction in size. Since 1963 more than half of the area melted. Harris (2002) states that *"an isolated case of thermokarst is a poor indicator of climatic change"* which I fully agree with. But at Haukskardsmyra, not only one palsa is decaying, and despite the existence of small embryo palsas, the entire bog shows a trend towards degeneration.

A similar development is reported from the palsa bogs near Haugtjørnin, where most of the palsas are heavily affected and only a few seem to be stable (Sollid and Sørbel 1974). On figure 42 and 43 the development of a palsa plateau from 1974-2006 is shown. In 1974 most of the palsas in the bog had already disappeared and only this palsa remained – may be due to the somewhat lower water level on the fringe of the bog. Two ponds were established along the sides and another developed on the palsa surface. Until 2006 nearly the entire palsa had melted. The melting of the last palsa in this pond indicates that also in this area, the climatic conditions are neither sufficient for palsa survival nor palsa regeneration. At Einunndalen, a relict palsa bog can be found which was completely extinct in 1963 (Sollid and Sørbel 1998). When exactly the palsas in this bog melted is unknown, but it implies area stopped having favourable conditions for palsas already some time ago. Matthews et al (1997) reports about mineral frost mounds at Leirpullan where most of them are in a degraded state.

Jelmert (1978), Lie (1996) and Sollid and Sørbel (1998) conclude that the entire Dovrefjell area is dominated by receding permafrost features and no new, more permanent features could develop over the last decades. This picture has not changed since then and I therefore interpret Location 4 to likely reflect the situation of the entire region.

Degradation of palsa bogs have also been reported from other regions in Fennoscandia. Lindqvist (1995) observed a palsa bog near Karlebotn, near Varangerfjorden which was characterised by degradation from 1965 on. In Corgosjokka, Northern Norway, circular lakes indicate collapsed or collapsing frost mounds. Field investigations as well as the study of aerial photographs indicate that the entire area is dominated by remnants or fossil forms (Svensson 1969). Svensson (1969) concluded that the missing insulating peat layer results in a greater sensibility to the registered higher MAAT of this area, which explains the fast break-down of these features. The size of the palsas in Sweden's most southerly palsa bog in Laivadalen, southern Lapland was reduced by 50% in the period from 1960-1997 (Zuidhoff and Kolstrup 2000). The bog is characterized by decaying features and neither there, new long-living palsas developed during the last decades (Zuidhoff and Kolstrup 2000). Luoto and Seppälä (2003) modelled the former distribution of palsa mires in a 95 km long north-south transect area in Northern Finland. They calculated the area of former palsa distribution to be about three times larger than at present. Most of the degradation occurred in the marginal southerly distribution areas.

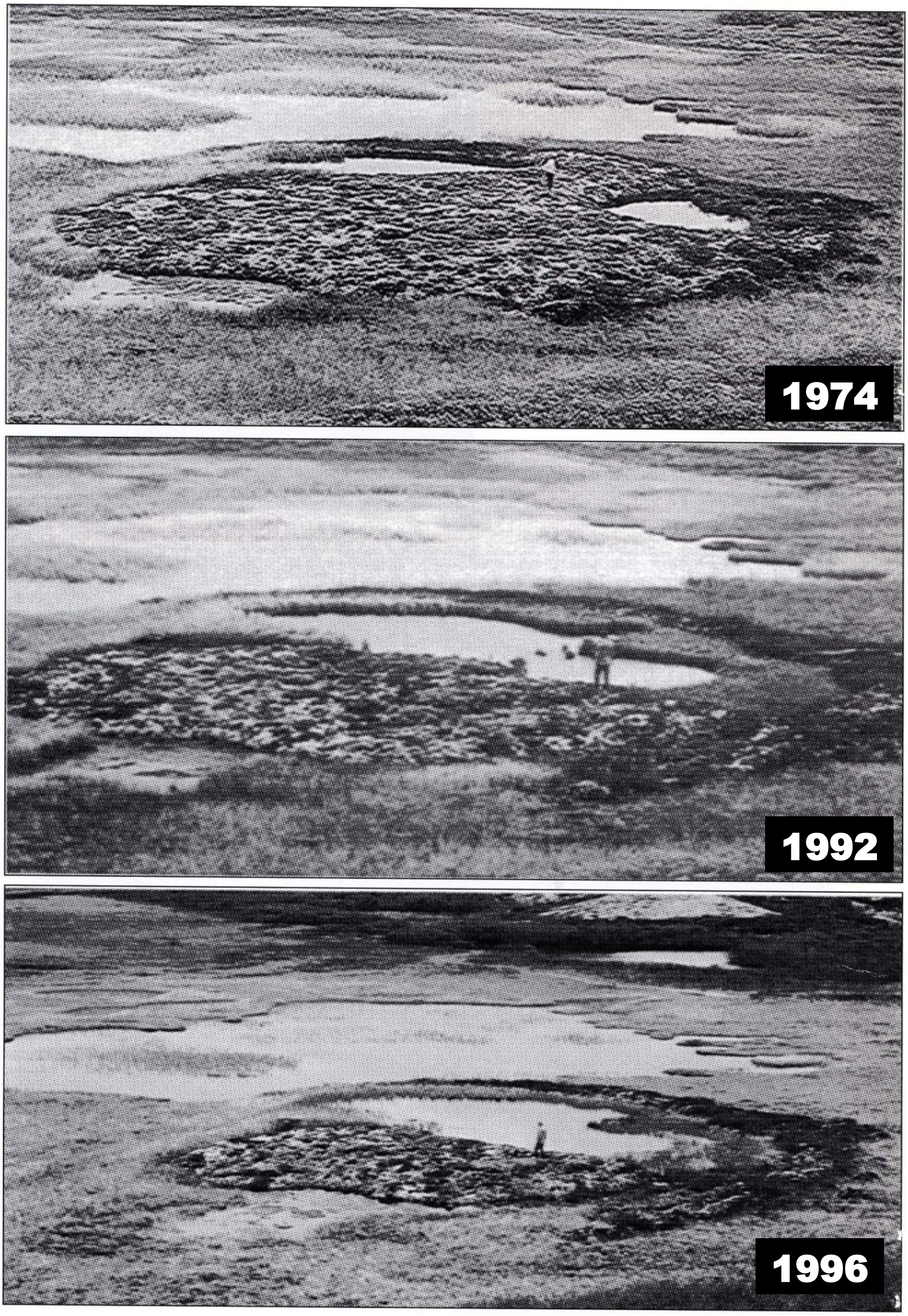


Figure 42 A palsa plateau near Haugtjørnin. Photos taken 1974, 1992 and 1996 (Lie 1996).

Figure 43 A palsa plateau near Haugtjørnin. Photo from 2006 (Photo: Leif Sørbel).

Thickening of the active layer, warming and loss of permafrost is documented from the Torneträsk region in northernmost Sweden. Permafrost disappeared at 81% of the sampling points (Åkerman and Johansson 2008).

Svensson (1969), Zuidhoff and Kolstrup (2000) and Luoto and Seppälä (2003) conclude MAAT and precipitation to be the main controlling factors for present palsa existence and their future survival. The MAAT in Northern Europe is predicted to increase by 2.2°-5.3°C until the end of the 21st century and also the total amount of precipitation will rise substantially (IPCC 2007) which makes the future occurrence of palsas in Fennoscandia unlikely.

All the above authors expect the distribution of palsa bogs to reduce. This presumption is met by Fronzek et al. (2006) who modelled the future distribution of palsas near the limit of permafrost in Fennoscandia. Fronzek calculated the area which is climatically suitable for palsa development to shrink considerably, also with a small increase of MAAT (1°C) and precipitation (10%). Furthermore, all but one climate scenario would result in the complete disappearance of suitable regions for palsa development by the end of the 21st century.

Due to the marginal position of Haukskardsmyra at Dovre, the bog is highly sensitive to even small changes in climate. At present, the collapse of this mire due to warming and increase of precipitation during the last century can be monitored. From the volume loss of the palsas since the middle of the last century it can be estimated that it will take further 30-50 years until all palsas have melted.

6.6 Which further investigations can be done?

Permafrost is known to thin out from below but few studies have been carried out on palsas (Seppälä 1990, Zuidhoff 2002). Therefore, it is suggested to accomplish further investigations on the thickness of the permafrost beneath a palsa, the temperature within the permafrost, subsequently the rate of the thawing from below and their relation to the break-down of a palsa from the sides. This can give valuable information about the temperature regime at the time degeneration starts and in consequence, about the required time span to level such a permafrost landform.

Furthermore, the quality of satellite images steadily improves and therefore constitutes an interesting alternative to aerial photographs. Most likely, satellite images will gain in importance in future.

The current project "Overvåkning av palsmyr" from the Norsk institutt for naturforskning (NINA) which includes the long-term monitoring of four areas harbouring palsa bogs in northern Norway as well as in Dovrefjell offers the opportunity to compare bogs from different environmental settings and detect their response to climate warming.

7 Conclusion

Block erosion and thermokarst are the main destructive factors for the palsa at Location 4 and caused the rapid recent degeneration of the palsas' northern part. Probably, intensive erosion will proceed and lead to the collapse of the entire palsa within a few years.

Break-down since 1955 is documented but the break-down is likely to have started long before. The main factors for palsa degradation are most likely an increased MAAT and precipitation during the 20th and perhaps also the 19th century. It is likely that thawing started sometime before the warmer period during the 1930s, maybe as early as after the Little Ice Age. That the average MAAT during the last 40 years at the palsa bog was just above 0°C and also unfavourable long before that implies that palsas have a slow response time. They do not disappear within a few years because their frozen core needs many decades to melt completely.

There is no evidence of any cyclic evolution in this palsa bog and although small embryo features have been observed, their life time is limited to only a few years. Such temporarily forms appear under favourable conditions after a few consecutive winters with low temperatures and little snow and reflect recent climatic variations.

The entire palsa bog is not in equilibrium with the present local climate and is characterized by a clear trend towards decay. Today, the mire is situated out of the climatic range for palsa development and depending on the rate of thaw is likely to disappear within 30-50 years.

Most probably the decay of the palsas at Haukskardsmyra represents the situation for the entire Dovre region, where palsa degradation trends are documented.

This leads to the conclusion that palsas can be used as climate indicators, if

A. not only one feature but a region is observed over a certain period of time and

B. the climate perturbation lasts long enough for the palsa bogs to respond.

Reference list

ACIA. 2005. *Artic Climate Impact Assessment - Scientific report*. Cambridge. Cambridge University Press.

Åhman, R. 1976. The structure and morphology of minerogenic palsas in northern Norway. *Biuletyn Peryglacjalny* 26, 25-31.

Åhman, R. 1977. *Palsar i Nordnorge: en studie av palsars morfologi, utbredning och klimatiska förutsätningar i Finnmarks och Troms fylke*, Lunds universitet, Geografiska institutionen, Lund. 165 pp.

Åkerman, H.J. and Johansson, M. 2008. Thawing permafrost and thicker active layers in sub-arctic Sweden. *Permafrost and Periglacial Processes* 19, 279-292.

Follestad, B.A. and Fredin, O. 2006. Late Weichselian ice flow evolution in south-central Norway. *1st TopoNorge Workshop on Geological Survey of Norway*, Mar 06-07, Trondheim, NORWAY, 281-289.

French, H.M. 1996. *The Periglacial Environment*, Essex: Longman. 340 pp.

Fries, T. and Bergström, E. 1910. Några iakttagelser öfver palsar och deras förekomst i nordligaste Sverige. *Geol Fören Förhandl, Stockholm* 32, 195-205.

Fronzek, S., Luoto, M. and Carter, T.R. 2006. Potential effect of climate change on the distribution of palsa mires in subarctic Fennoscandia. *Climate Research* 32, 1-12.

Gorham, E. 1991. Northern peatlands: role in the carbon cycle and probable responses to climatic warming. *Ecol Applic* 1, 182-195.

Harris, S.A. 1982. Identification of permafrost zones using selected permafrost landforms. *In* French, H.M. (ed). *Proceedings Fourth Canadian Permafrost Conference* National Research Council of Canada, Ottawa, 49-58.

Harris, S.A. 1986. *The permafrost environment*, London: Croom Helm. 276 pp.

Harris, S.A. 1993. Palsa-like mounds developed in a mineral substrate, Fox Lake, Yukon Territory. *Sixth international conference on Permafrost Beijing CHN China*, Beijing, China, Wushan Guangzhan, China: South University of Technology Press, 238-243.

Harris, S.A. 1998. A genetic classification of the palsa-like mounds in Western Canada. *Biuletyn Peryglacjalny* 37, 115-130.

Harris, S.A. 2002. Causes and consequences of rapid thermokarst development in permafrost or glacial terrain. *Permafrost and Periglacial Processes* 13, 237-242.

IPCC. 2007. *The Physical Science Basis - Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge. Cambridge University Press.

Jelmert, L.T. 1978. *Utvalgte periglasialformer på Dovrefjell*, Geografisk Institutt, Universitetet i Oslo, Oslo. 121.

Juliussen, H. and Humlum, O. 2007. Preservation of block fields beneath Pleistocene ice sheets on Solen and Elgahogna, central-eastern Norway. *Zeitschrift fuer Geomorphologie* 51, 113-138.

Kleman, J. and Hättestrand, C. 1999. Frozen-bed Fennoscandian and Laurentide ice sheets during the last glacial maximum. *Nature London* 402, 63-66.

Lie, K. 1996. *Palsstudier i Sør-norge*, Geografisk Institutt, Universitetet i Oslo, Oslo. 81.

Lindqvist, S. 1995. Palsar som klimatindikatorer. *Svensk geografisk årsbok* 71, 91-95.

Lundqvist, G. 1951. En palsmyr sydöst om Kebnkaise. *Geol Fören Förhandl, Stockholm* 73, 209-225.

Lundqvist, J. 1962. Patterned ground and related frost phenomena in Sweden. *Sveriges Geol Undersökning, Ser C,* 583, 101p.

Lundqvist, J. 1969. Earth and ice mounds: A terminological discussion. *In* Péwé, T.L. (ed). *The Periglacial Environment, Past and Present*. Montreal: McGill-Queen's University Press.

Luoto, M. and Seppälä, M. 2003. Thermokarst ponds as indicators of the former distribution of palsas in Finnish Lapland. *Permafrost and Periglacial Processes* 14, 19-27.

Luoto, M.J., Fronzek, S.J. and Zuidhoff, F.S.J. 2004. Spatial modelling of palsa mires in relation to climate in northern Europe. *Earth surface processes and landforms* 29, 1373-1387.

Matthews, J.A., Dahl Svein, O., Berrisford Mark, S. and Nesje, A. 1997. Cyclic development and thermokarstic degradation of palsas in the mid-Alpine zone at Leirpullan, Dovrefjell, southern Norway. *Permafrost and Periglacial Processes* 8, 107-122.

Nesje, A., Dahl, S.O., Anda, E. and Rye, N. 1988. Block fields in Southern Norway; significance for the late Weichselian ice sheet. *Norsk Geologisk Tidsskrift* 68, 149-169.

Nihlen, T. 2000. Palsas in Harjedalen, Sweden: 1910 and 1998 compared. *Geografiska Annaler Series A: Physical Geography* 82A, 39-44.

Pissart, A. 2002. Palsas, lithalsas and remnants of these periglacial mounds. A progress report. *Progress in Physical Geography* 26, 605-621.

Rapp, A. 1982. Zonation of permafrost indicators in Swedish Lapland. *Norsk geografisk Tidskrift* 82, 37-38.

Salmi, M. 1970. Investigations on palsas in Finnish Lapland. *Ecology of the subarctic regions - Proceedings of the Helsinki Symposium 1966*, Unesco Paris France, Paris, 143-153.

Seppälä, M. 1972. The term "palsa". *Zeitschrift fuer Geomorphologie* 16, 463.

Seppälä, M. 1976. Seasonal thawing of a palsa at Enontekio, Finnish Lapland, in 1974.; The Aberystwyth symposium, 1975. *Biuletyn Peryglacjalny*, 17-24.

Seppälä, M. 1982a. An experimental study of the formation of palsas. *In* French, H.M. (ed). *Proceedings Fourth Canadian Permafrost Conference* National Research Council of Canada, Ottawa, 26-42.

Seppälä, M. 1982b. Palsarnas periodiska avsmaeltning i Finska Lappland. *Geografisk Tidsskrift* 82, 39-44.

Seppälä, M. 1983. Seasonal thawing of palsas in Finnish Lapland. *Permafrost: Fourth International Conference, Proceedings*, National Academy Press, Washington, D. C., 1127-1132.

Seppälä, M. 1986. The origin of palsas. *Geografiska Annaler Series A: Physical Geography* 68, 141-147.

Seppälä, M. 1988a. Frozen peat mounds in continuous permafrost, northern Ungava Quebec, Canada. *In* Koster Eduard, A. and French Hugh, M. (eds). 71: Gebrueder Borntraeger Berlin-Stuttgart Federal Republic of Germany., Zeitschrift fuer Geomorphologie Supplementband. 71, 107-116.

Seppälä, M. 1988b. Palsas and related forms. *In* Clark, M.J. (ed). *Advances in Periglacial Geomorphology*. Chichester: Wiley, 247-278.

Seppälä, M. 1990. Depth of Snow and Frost on a Palsa Mire, Finnish Lapland. *Geografiska Annaler Series A: Physical Geography* 72, 191-201.

Seppälä, M. 1995. How to make a palsa: a field experiment on permafrost formation. *Zeitschrift fur Geomorphologie, Supplementband 99*, 91-96.

Seppälä, M. 2003. Surface abrasion of palsas by wind action in Finnish Lapland. *Geomorphology* 52, 141-148.

Seppälä, M. 2004. *Wind as a geomorphic agent in cold climates*, Cambridge: Cambridge University Press. 358 pp.

Sollid, J. 1975. Landskapet. *In* Gjærevoll, O. and Ryvarden, L. (eds). *Dovrefjell Omtjernkampen*. Oslo: Luther Forslag A/S.

Sollid, J.L. and Sørbel, L. 1974. Palsa bogs at Haugtjørnin, Dovrefjell, South Norway. *Norsk geografisk Tidsskrift*, 53-60.

Sollid, J.L. and Sørbel, L. 1994. Distribution of glacial landforms in Southern Norway in relation to the thermal regime of the last continental ice sheet. *Geografiska Annaler Series A: Physical Geography* 76, 1-2.

Sollid, J.L. and Sørbel, L. 1998. Palsa bogs as a climate indicator - Examples from Dovrefjell, southern Norway. *Ambio* 27, 287-291.

Sørbel, L. and Tolgensbakk, J. 2006. *HJERKINN 1519 III - kvartærgeologisk kart M 1:50 000*. Institutt for geofag, Universitetet i Oslo.

Svensson, H. 1962. Några iakttagelser från palsområden. Flybildanalys och fältstudier i nordnorska frostmarksområden. *Norsk geografisk Tidskrift* 18.

Svensson, H. 1969. A type of circular lakes in northernmost Norway. *Geogr Ann Ser A* 51, 1-2.

Thorhallsdottir, T.E. 1994. Effects of Changes in Groundwater Level on Palsas in Central Iceland. *Geografiska Annaler Series A: Physical Geography* 76, 161-167.

Van Everdingen, R.O. 1988. *Multi-language glossary of permafrost and related ground-ice terms in Chinese, English, French, German, Icelandic, Italian, Norwegian, Polish, Romanian, Russian, Spanish and Swedish*. International Permafrost Association, University of Calgary. 272 pp.

Washburn, A.L. 1979. *Geocryology: a survey of periglacial processes and environments*, London: Edward Arnold. 406 pp.

Washburn, A.L. 1983. What is a palsa? *Proceedings 35, Akademie der Wissenschaften; Symposium*, Goettingen DEU Federal Republic of Germany, 35, 34-47.

Wramner, P. 1967. Studier av palsmyrar i Laivadalen, Lappland. *Medd fr Göteborgs Univ Geogr Inst* 86.

Wramner, P. 1973. Palsmyrar i Taavavuoma, Lappland *GUNI Rapport 3, Göteborgs Univ Nat geo inst*, 140 pp.

Zoltai, S.C. 1993. Cyclic Development of Permafrost in the Peatlands of Northwestern Alberta. *Arctic and alpine research* 25, 240-246.

Zuidhoff, F., S. and Kolstrup, E. 2005. Palsa development and associated vegetation in northern Sweden. *Arctic, Antarctic, and Alpine research* 37, 49-60.

Zuidhoff, F.S. 2002. Recent decay of a single palsa in relation to weather conditions between 1996 and 2000 in Laivadalen, northern Sweden. *Geografiska Annaler Series A: Physical Geography* 84A, 103-111.

Zuidhoff, F.S. and Kolstrup, E. 2000. Changes in palsa distribution in relation to climate change in Laivadalen, northern Sweden, especially 1960-1997. *Permafrost and Periglacial Processes* 11, 55-69.

Contents of the Appendix CD

Appendix A

Mean monthly temperatures 1923-2008

Appendix B

Includes all graphs displaying mean monthly precipitation 1923-2008

Appendix C

Includes all wind rose diagrams 1938-2005

Appendix D

Includes all data of low quality from 2006

Appendix E

Includes all regression analyses

Appendix F

Includes the snow depth profile E